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Quantifying the Effectiveness of Cedar Revetment in Mitigating Bank Erosion in Riceford Creek, Minnesota

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QUANTIFYING THE EFFECTIVENESS OF CEDAR REVETMENT IN MITIGATING BANK EROSION IN RICEFORD CREEK, MINNESOTA

A Master's Thesis

Presented to

The Graduate College of

Missouri State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geospatial Sciences

By

Talia A. Klein

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QUANTIFYING THE EFFECTIVENESS OF CEDAR REVETMENT IN MITIGATING BANK EROSION IN RICEFORD CREEK, MINNESOTA

Geography, Geology and Planning

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ABSTRACT

Southeastern Minnesota has incised streams that are susceptible to bank erosion. Previously, efforts have been made to identify sections of Riceford Creek that have high erosion susceptibility using the Bank Erosion Hazard Index (BEHI). Locally harvested cedars were then used as a revetment strategy to mitigate erosion of the stream banks prioritized by the BEHI analysis. This study aims to 1) determine if cedar revetment effectively mitigates bank erosion in Riceford Creek and 2) determine if the BEHI method is an effective way of quantifying erosion hazard in Riceford Creek. This study focuses on two sections in Riceford Creek where cedar revetments have been installed. A detailed stream survey and aerial photography were collected in Spring 2016. A large flood occurred in September 2016, consequently additional aerial photography was collected in Spring 2017, followed by another detailed survey in Summer 2017. The imagery reveals multiple areas in Riceford Creek where the revetments are starting to be buried by sediment (effective) as well as areas where the revetment appears to have been washed out (ineffective). This study provides both visual and quantitative data on how effective the revetment was at mitigating bank erosion during the 2016 flood.

KEYWORDS: Minnesota, cedar revetment, rivers, stream bank erosion, fluvial geomorphology, revetment failure, revetment success, Rosgen’s BEHI

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INTRODUCTION

The Root River in southeastern Minnesota is a tributary of the Mississippi River (Fig. 1). Portions of the Root River have been designated by the Minnesota Pollution Control Agency (MPCA) as impaired for turbidity under the guidelines of section 303d of the U.S. Clean Water Act (EPA, 2010). Turbidity is a measure of the clarity or haziness of a fluid, caused by suspended particulates in the fluid. In this case turbidity is an indicator of water quality. Agricultural production is intimately related to surface water quality in southeastern Minnesota. The agronomic practices and management choices made on farms have direct impacts on the quality of downstream surface water streams. Agriculture plays a very large role in the economy of Minnesota, in general, and the Root River watershed in particular, with 71% of the Root River Watershed in agricultural production (MPCA, 2012).

Although agriculture plays a big role in both the economy and culture of greater Minnesota, Minnesotans also tend to place a high value on the quality of their natural and water resources. This is evidenced by the broad support of voters for the passage of the "Clean Water, Land and Legacy Amendment" to the Minnesota Constitution in 2008. According to Minnesota's Legacy: About the Funds (www.legacy.mn.gov/about-funds) the amendment increased the sales tax and directed 33% of the new tax revenue directly to restoring water quality in lakes, streams and rivers, and protecting groundwater. An additional 33% is allocated to enhancing natural lands and wildlife habitats, with small portions also set aside to support the arts, cultural heritage, and parks and trails.

Recently the legislature and governor also passed a buffer law that requires a vegetated buffer between the edge of cultivation in crop fields and the bank of adjacent streams. A

significant source of sediment in streams is erosion from agricultural fields, which is exacerbated when row crops are planted right up to the stream's edge (Fig. 2). These increased sediment loads increase the amount of suspended solids in streams, which in turn increases turbidity and degrades aquatic habitats.

Along with agriculture, the Root River watershed includes a number of tributary streams with world class trout fishing that draws anglers both locally and from far away. Richey (2015) with Minnesota Conservation states that Minnesota sells more fishing permits than any other state per capita, with approximately 83,000 trout stamps. Consequently, Sport fishing makes a significant contribution to the multi-billion-dollar tourism industry in Minnesota in general, and in southeastern Minnesota specifically. The high quality of the fishing is dependent on the health of the streams and waterways. The naturally spring-fed streams keep the rivers in southeastern Minnesota cold through the summer and make it possible to sustain a trout fishery that meets the demand for sport anglers.

All trout require cold, clear, fast moving water to survive, and gravelly substrate in which to lay eggs, but the brook trout, which are native to the area, are the most susceptible to changes in their environment (Saila, Lewis, Cheeseman, and Poyer, 2004). Brook trout require a water temperature below 25º C and have very low tolerance to sediment in the stream. Due to their intolerance of contaminants, brook trout are found near the headwaters of streams, while brown and rainbow trout, which are more tolerant species introduced to the area, are often more abundant farther downstream. With over 10,480 kilometers of designated trout streams and tributaries in Minnesota (Melotik), multiple groups and agencies are involved with the effort of protecting and restoring trout habitat, especially in headwater streams.

Minnesota Trout Unlimited (MNTU) is one such group that actively works to mitigate erosion along streams by stabilizing the banks. Its mission is to "conserve, protect, restore, and sustain Minnesota's coldwater fisheries and their watersheds" (mntu.org). A combination of cost, time, and labor-intensive stabilization strategies along with other factors limits the amount of stream bank that is treated each year by MNTU and other groups. MNTU was established in 1959 and since then they have stabilized approximately 105 kilometers of stream banks. This averages out to 1.8 kilometers of stream bank treatments each year. If this rate of work continues, it would be 6,000 years before just designated trout streams would be fully treated, assuming the strategies used are effective with the first installation and don't need maintenance.

Common bank stabilization strategies can cost up to several hundred dollars per foot of stream bank treated. They are often labor intensive and require major re-working of stream banks, often in the form of digging back from the bank to make the bank slopes less steep. MNTU has project reports which illustrate this point. One example is their work in Hay creek, which took place from 2008 to 2013 and required sloping and stabilization of banks as well as installation of weirs, erosion blankets, and other structures (MNTU.org/hay-creek/). Even with volunteer labor, costs for equipment, materials, and professional guidance quickly add up. Considering there are more than 83,000 miles of stream in Minnesota (MPCA), a faster and more cost friendly approach to bank stabilization is needed. One alternative is cedar revetments which only cost tens of dollars per foot of stream bank.

Cedar revetments work by stabilizing the toe of eroding banks and allowing the banks to become shallower over time by natural slumping to a stable angle of repose Although cedar revetments are being put in place in streams across the US (Barden, 2003; Fox, Goodman, and Teel, 2004; Siefken 1992), there are few studies evaluating the long-term effectiveness of the

revetment strategy. The only literature found documenting how a stream changed, with those changes being directly attributed to the cedar revetment, was done by Siefken (1992) in north-central Nebraska on a sandy stream. Siefken (1992) found that the cedar revetment, in combination with planting reed canary grass, worked to narrow the stream channel and increase stream velocity, allowing the stream to flush excess sediment from the channel and uncover the gravel substrate within 2 to 3 years. Although narrowing and deepening the channel is not always desirable, these were very favorable results for the area. Lave (2009) points out the scarcity of information on how most stream restorations perform and discusses the need for comparative studies of multiple stream restoration techniques across the nation. More research to evaluate how cedar revetments work in different areas and conditions will help fill that need.

In 2013 Dr. Toby Dogwiler and several of his students at Winona state University started working with the Soil and Water Conservation District (SWCD), the local Corn Growers Association and local farmers to prioritize reaches of Riceford Creek, a tributary of the Root River, for bank stabilization using cedar revetments. Revetments were placed and monitored for effectiveness in several trial reaches along Riceford Creek, part of which is a designated trout fishing stream (Fig. 3.). Revetments were placed in Lea reach the first year and then directly downstream in Sinclair over the second (2014) and third years (2015). The work moved about 6.8 kilometers downstream to the Breitenbach reach during the third and fourth years (2015/2016). Each summer, as more farmers came on board with the program, more parts of Riceford Creek were assessed for revetment. During that time, there were no techniques for identifying and prioritizing stream banks for effective placement of cedar revetments. It was a matter of waiting to see where revetments would be most effective or not effective, and it was determined that an in-depth study of the area was needed to inform revetment placements in

subsequent years. A study focusing on the Lea and Sinclair reaches of Riceford Creek was begun in Spring 2016 to track quantitative changes to a stream with cedar revetments. Observations were recorded three times between spring 2016 and summer 2017 and used to document changes to the stream during a flood in Fall 2016.

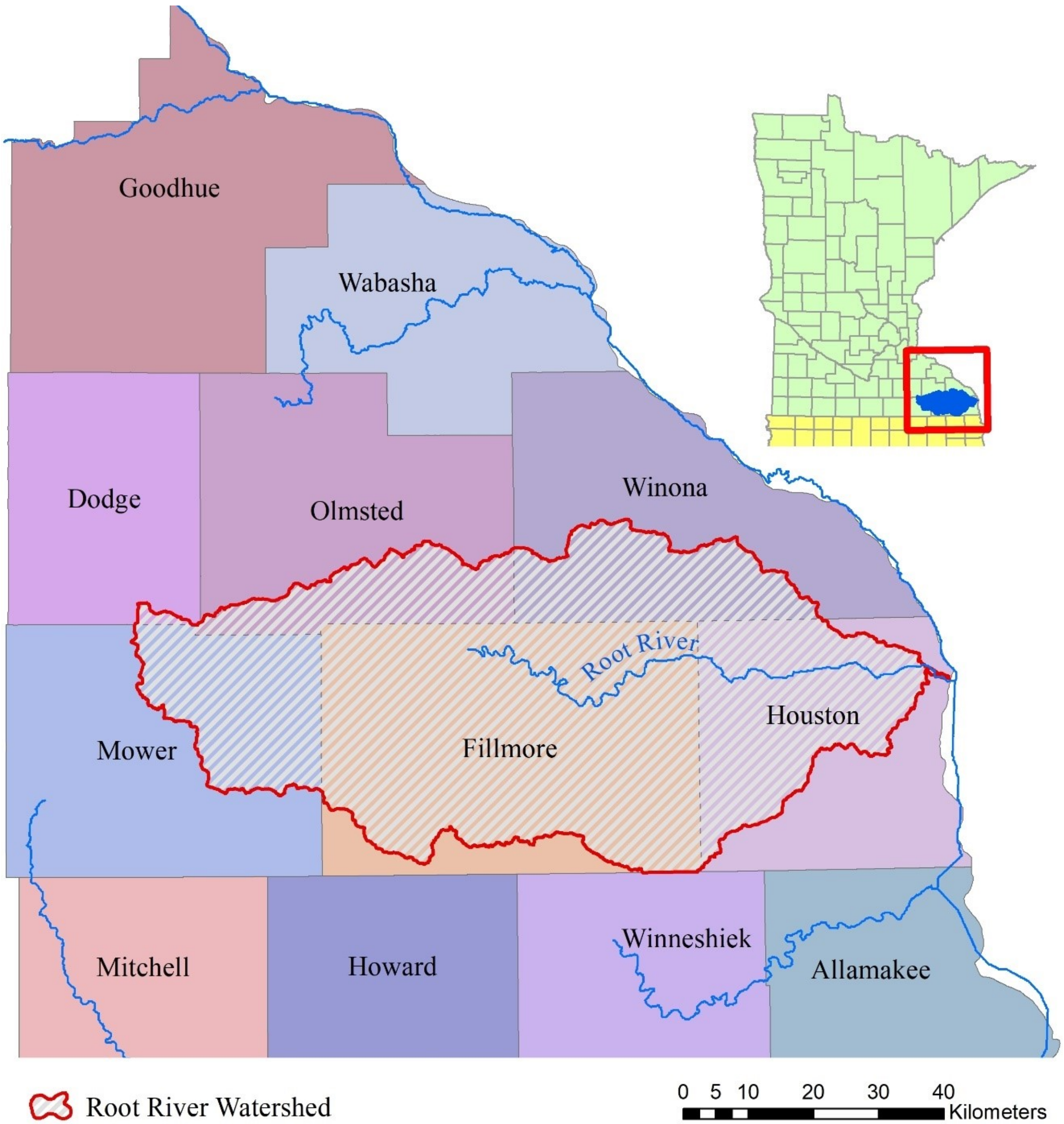


Figure 1. Map of the Root River watershed in Southeastern Minnesota. The Root River is a tributary of the Mississippi River.

Figure 2. Planting crops directly by stream banks without a buffer exacerbates erosion and was common before buffer laws were adopted. Picture taken in Southeastern Minnesota in September 2013 by Toby Dogwiler and Kat Schroeder.

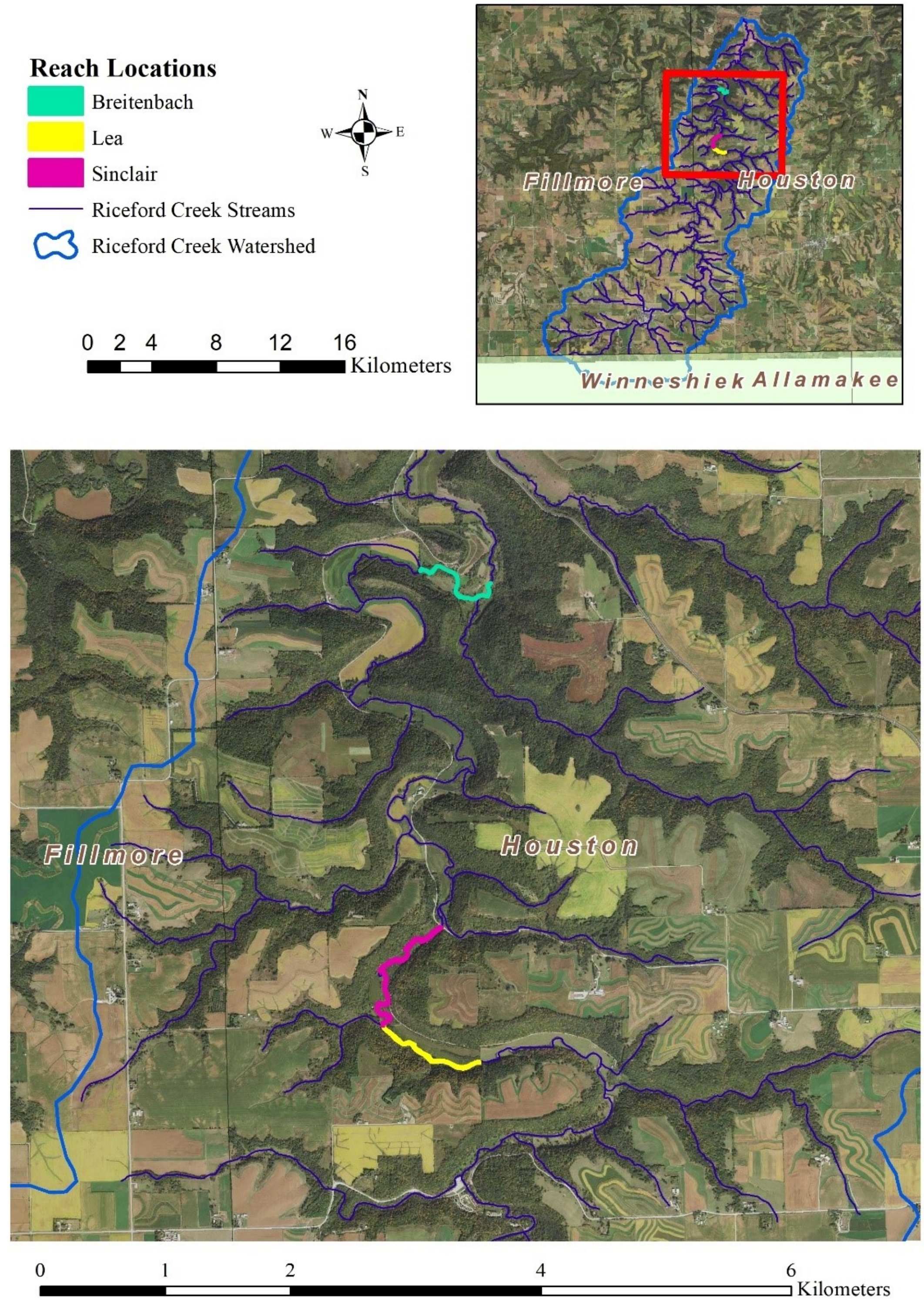


Figure 3. The three reaches in Riceford Creek that were surveyed and treated with revetments from 2013 to 2016 (Lea 2013, Sinclair 2014, Breitenbach 2015/16).

BACKGROUND

Study Area

Riceford Creek is an upland tributary of the Root River in eastern Houston County, Minnesota (Fig. 4). The Root River drainage basin covers approximately 1,660 km^2 in the six most southeastern counties in Minnesota as well as part of northeastern Iowa (Dogwiler, 2010). Riceford Creek is in the Driftless Area physiographic province (Fig. 5) which gets its name from the apparent lack of glaciation in the region during the late Pleistocene ice advances (Hobbs, 1999; Knox and Attig, 1988; Lusardi, 1997; Mickelson, Knox, and Clayton, 1982). Much of the Minnesota portion of the Driftless Area shows evidence of glaciation during the earliest Pleistocene (Chamberlin and Salisbury, 1885; Hobbs, 1999). However, the drift deposited during that time, as well as other evidence of glaciation, have been erased by erosion and surface processes working on the landscape during the remainder of the Pleistocene (Chamberlin and Salisbury, 1885; Knox and Attig, 1988).

The geomorphology of the Driftless Area is largely a result of continued glaciation around its edges during the late Pleistocene. Knox (1985) and Leigh and Knox (1994) explain how the surrounding glaciers accelerated mass wasting in the Driftless Area due to frost action and resulted in deep colluvial deposits in the valleys. Knox (1989) describes how overland flow then became dominant with the subsequent shift to a warmer, more humid, climate during the Holocene. The fluvial processes from melting glaciers and precipitation derived from air circulation from the Gulf of Mexico flushed much of the stored colluvial sediment from the valleys (Knox, 1989; Leigh and Knox, 1994; Mickelson et al., 1982). Associated changes with vegetation resulted in much less sediment coming from upland hillslopes (Knox, 1989; Leigh

and Knox, 1994). As a result, the Driftless Area is now characterized by steep bluffs, deep valleys, and rolling uplands (Chamberlin and Salisbury, 1885; Knox and Attig, 1988; Trimble and Lund, 1982).

Before the Treaty of Mendota opened southern Minnesota to European settlement in 1851, much of the land in the Driftless Area consisted of either oak forest or bur oak savannas, with sugar maple-basswood forests on the steepest slopes (Albert, 1995; Knox, 1977; Lueth, 1994). On the steep, south-facing bluffs across southeastern Minnesota, there are also xeric tallgrass prairies with native plant communities that were historically maintained by natural fires and intentional burning (Albert, 1995; McAndrews, 1966). Xeric prairies are open, non-forested areas with shallow, rocky soils dominated by plant communities needing very little water and are locally referred to as "goat prairies." After fire suppression, eastern red cedars started invading these prairies (Bragg and Hulbert 1976; Briggs, Hoch, and Johnson, 2002a; Hoch and Briggs 1998; Ormsbee, Bazzaz, and Boggess, 1976). After 1851, European settlers converted most of the land into cropland and pastures. The farming practices the settlers used to cultivate fields included planting up and down the steep valley slopes (Fig. 6) and resulted in substantial erosion of the uplands (Happ, Rittenhouse, and Dobson, 1940; Sartz, 1976).

In many places 0.5 m to 4 m of sediment was lost from the uplands and deposited in river valleys during this time (Knox, 1977; Knox, 2006). These sediments are referred to as "legacy sediments", which reflects the idea that their deposition was caused by poor land use practices during the early post-settlement period. The "legacy" of those land uses—these floodplain sediments—still have huge effects on the geomorphology and fluvial processes of modern stream networks. The abrupt addition of so much sediment to the river valleys caused many of the streams to fall out of equilibrium with unstable banks, loss of land in the floodplain, and a

swiftly changing channel and valley morphology. Today, the stream network has many deeply incised channels carving away, via bank erosion, at these legacy sediments, resulting in a significant volume of suspended sediments in Driftless Area streams (Trimble and Lund, 1982). In addition, current farming practices in Minnesota still utilize moderately steep slopes for row crops and are often susceptible to field erosion (Dogwiler, 2010).

The Riceford Creek watershed is situated within the dissected plateau of the Driftless Area, comprised of Ordovician dolomite, limestone, and sandstone bedrock overlain by meters to tens of meters of soil (Dogwiler, 2010). Riceford Creek is representative of the watershed. It is incised in a wide river valley filled with legacy sediment on the flood plains (Fig. 7). Current land cover along Riceford Creek consists mostly of row crops and pasture, though forests still cover areas where the hills are too steep for farming (Fig. 8).

Juniperus Virginiana (Carl Linnaeus) is referred to in most literature (and this thesis) as eastern red cedar, or red cedar. Eastern red cedar is native to every state in the Eastern United States from the Rocky Mountains to the Atlantic Coast (Burns and Honkala, 1990; Van Haverbeke and Read 1976). However, according to Bragg and Hulbert (1976) and Curtis (1959) cedars were not historically found near prairie borders. After settlement and the subsequent suppression of fires that previously maintained native species, red cedar began invading the prairies (Bragg and Hulbert 1976; Briggs and Gibson 1992; Briggs et al., 2002a, Briggs, Knapp, and Brock, 2002b; Engle and Kulbeth 1992; Hoch and Briggs, 1998; Ormsbee et al., 1976) contributing to the demise of the natural habitat of native prairie flora and fauna (Bragg and Hulbert 1976; Funk and Vitousek, 2007; Gehring and Bragg, 1992; Hoch and Briggs 1998; Knight, Kurylo, Endress, Stewart, and Reich, 2007).

Pierce and Reich (2010) describe various explanations for why native prairie species decline in the presence of red cedar and other woody invaders, as well as providing data that shows prairie communities can recover to a pre-invasion state relatively rapidly following cedar removal. The U.S. Fish and Wildlife Service, Minnesota Department of Natural Resources (MNDNR), The Nature Conservancy and other private partners have been working to remove invasive cedars and restore prairie habitats in Minnesota for several years (Chaplin and Van Vleck, 2014). Because cedars are naturally resistant to rotting and both plentiful and already being targeted for removal from the goat prairies, harvesting them to use as a low-cost resource for revetments provides an avenue to solve both problems.

In stream restoration, a revetment is any protective barrier that is placed on the stream bank. In order to be used as a revetment, cedars are harvested from the prairies. They are then laid on their side along the toe of eroding banks, lashed together end-to-end with steel cables, and anchored to the bank with duck bill anchors (Fig. 9). The revetments in this study were placed with the goal of reaching an anchor depth of 5-8 feet but actual depths varied due to rocky banks and occasional refusal layers.

Placing cedar revetments in front of stream banks in this manner is meant to serve two purposes: first, the cedars reduce the near bank velocity of the water by increasing bank roughness (i.e., Manning's n). This reduces the energy available to carry sediment away. Second, when a steep bank collapses above the cedars, the soil should become trapped in the branches of the trees instead of being swept into the stream. This will stabilize the toe of the bank, thereby mitigating lateral erosion processes while allowing the bank to become less steep (Fig. 10). Once the bank slope becomes less steep, grasses and other small vegetation are able to grow and their root systems anchor the soil and protect the stream bank from further erosion. Once a stable,

vegetated morphology develops the bank will continue to be stabilized even after the cedars have either decayed or been completely buried. This study was done, in part, to see if these goals are realized with cedar revetment.

Drone Imagery

The collection of high-resolution imagery by using drones, more formally referred to as small unmanned aerial systems, or sUAS, is becoming a more common scientific practice. Riceford Creek is a remote area and although governmental organizations and commercial imagery collection companies (such as Google Earth) have been acquiring regional-scale repeat photography in high resolution (1-3 m resolution) since the early 2000, the resolution is insufficient to accurately map small changes in stream bank position. To map changes in stream bank position before and after typical flood events requires a photo resolution that is greater than the typical amount of erosion that occurred.

For example, if erosion rates are approximately 10 cm for an event, then the photo resolution must be greater than 10 cm in order to see the change (e.g., 1-5 cm resolution) as indicated by the Nyquist Shannon sampling theorem (Shannon, 1949). sUASs provide an economical and rapid means of acquiring sub-decimeter resolution aerial imagery of field sites. Also, the regional-scale aerial imagery is often geared toward vegetation land cover classification and is thus acquired during “leaf-on” conditions. These image sets leave the stream banks hard or impossible to see because tree canopy obstructs the view. Using a sUAS enables acquiring imagery at much higher resolutions and for specific field sites. A sUAS also provides the opportunity to collect imagery “on demand,” such as before and after a project or after a significant event during conditions, such as leaf-off, that facilitate analysis of the desired targets. While image collection with a sUAS is relatively simple it can be affected by many

uncontrollable factors. Wind, rain, and extreme cold temperatures all affect flight and the electrical components of the sUAS. These adverse conditions can make it impossible to fly and collect data. Likewise, the angle of the sun and the presence or absence of cloud cover will greatly affect the image quality. The best time to take photos is when there is a thin cloud cover, as this reduces harsh shadows in the images, and makes processing and stitching photos more seamless. It is also necessary to have Ground Control Points (GCPs) located across the study area that are precisely located with differential GPS (dGPS) to allow georeferencing and orthorectification of the final image.

Previous Revetment Work in Riceford Creek

The initial cedar revetments in Riceford Creek were installed in the approximately 1 kilometer reach referred to as the Lea Reach in 2013 (south and upstream of the small bridge in Figure 11). Prior to the installation of the revetments a group from the Southeastern Minnesota Water Resources Center at Winona State University performed a detailed survey of the reach. The following year the work continued with a post-project survey of the Lea Reach. In 2014, a pre-survey was also conducted on the adjacent 1.5 kilometer downstream reach referred to as the Sinclair Reach (north and downstream of the bridge in Figure 11). That summer (2014) the team surveyed several cross-sections of the river, conducted a longitudinal survey, and both banks were given stability ratings using Rosgen's (2001) Bank Erosion Hazard index (BEHI) method (Tousignant, 2014).

Rosgen's (2001) BEHI method is a metric that assigns a numeric score and an adjective rating to a stream bank by estimating or quantifying various bank characteristics and using those results to calculate a final score. Ranges of scores are associated with adjective ratings that go

from “very low” up to an “extreme” hazard of erosion. BEHI is designed to be a rapid assessment, and easy to learn, making it possible for non-geomorphologists to quickly assess stream banks and obtain a meaningful estimate of their stability. BEHI involves measurement of bank angle, bank height, bankfull height, root depth, root density, and surface protection. Scores are also adjusted based on what material the banks consist of. The spreadsheet that was used to collect and calculate BEHI data can be seen in Figure 12.

Each summer (2013 for Lea and 2014 for Sinclair) the Minnesota Conservation Corps (MCC) was contracted to install cedar revetments based on the prioritization of banks derived from the pre-survey and BEHI analysis. The MCC was able to install revetments in 61% of the areas that had BEHI ratings of “Very High,” and 45% of the “High” hazard areas. They also revetted 12% of the “Moderate” hazard areas (Fig. 13). There were no “Extreme” or “Very Low” rated areas that received revetment treatment. As indicated in Dogwiler’s (2017) report, those areas with “Extreme” and “High” hazard ratings that did not receive revetments were deemed unsuitable candidates for treatment. One of the issues were reaches with very high (> 3.0 - 4.6 meter) banks. It was determined that stabilizing those banks would require some initial re-shaping with heavy machinery to get them to a point where the revetment would be feasible. The “Very Low” reaches did not receive treatment because the banks were already considered stable.

The process of surveying and revetment installation was repeated for the next 3 years in other reaches of Riceford Creek. This study was conducted in the Lea and Sinclair reaches because they were among the first areas treated in Riceford Creek and they have had the most time to influence the bank morphology. These reaches also happen to have the most easily accessible banks for the entire length of the stream, including several areas that have sparse canopy cover. This sparse cover was beneficial since a sUAS was used to collect imagery.

Another benefit of studying the Lea and Sinclair reaches is that there are numerous sections of bank where cedar revetments have been placed, as well as numerous untreated banks. The non-revetted areas serve as a control during observation and comparison of changes in areas with revetment to areas without revetment. Finally, the data collected and generated during the original surveys is easily accessible, which provides the opportunity to compare the current stream characteristics to those of the pre-revetment stream.

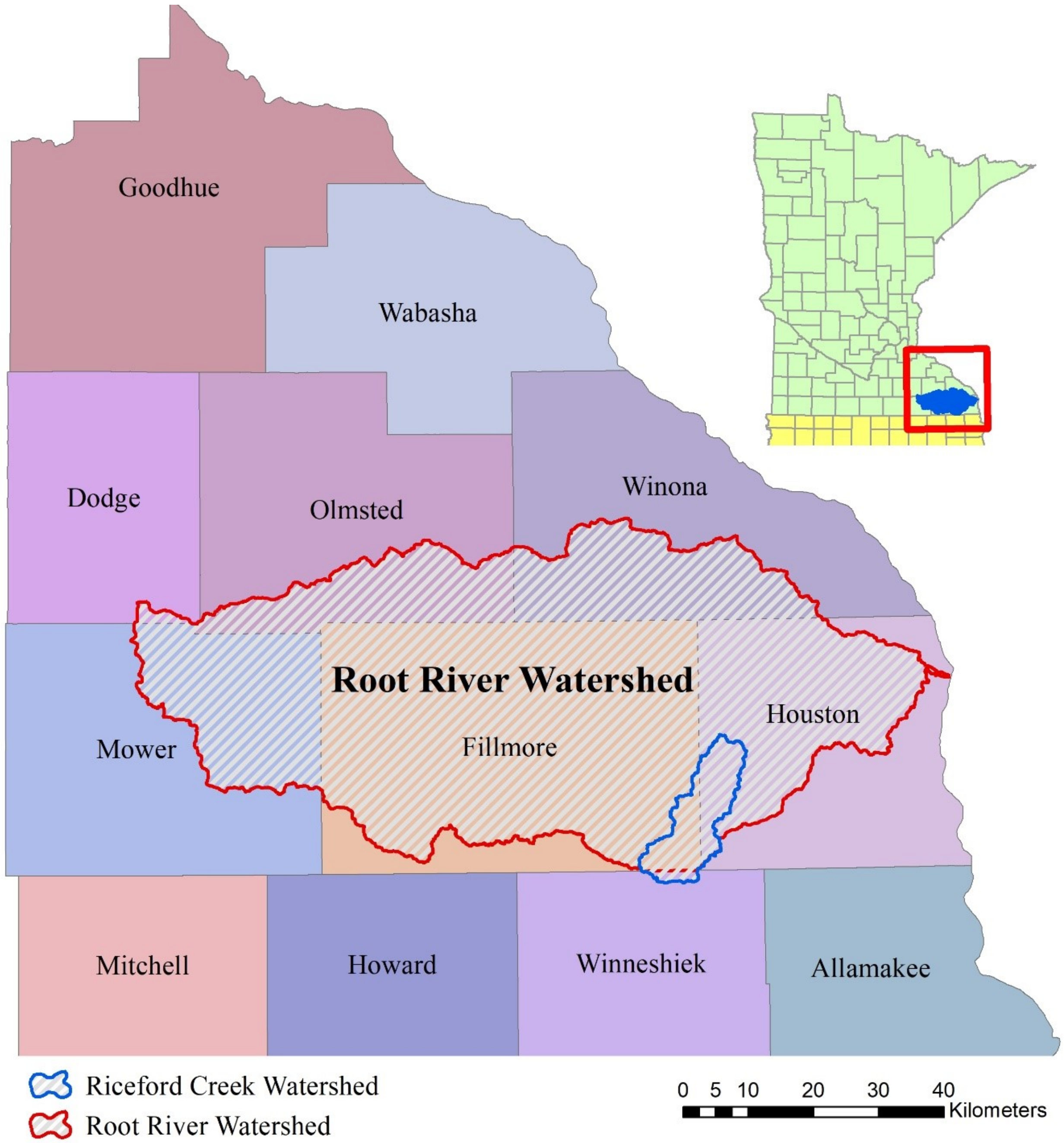


Figure 4. Placement of the Riceford Creek watershed within the Root River watershed. The most upstream portion of the Riceford Creek watershed is in Winneshiek County, Iowa.

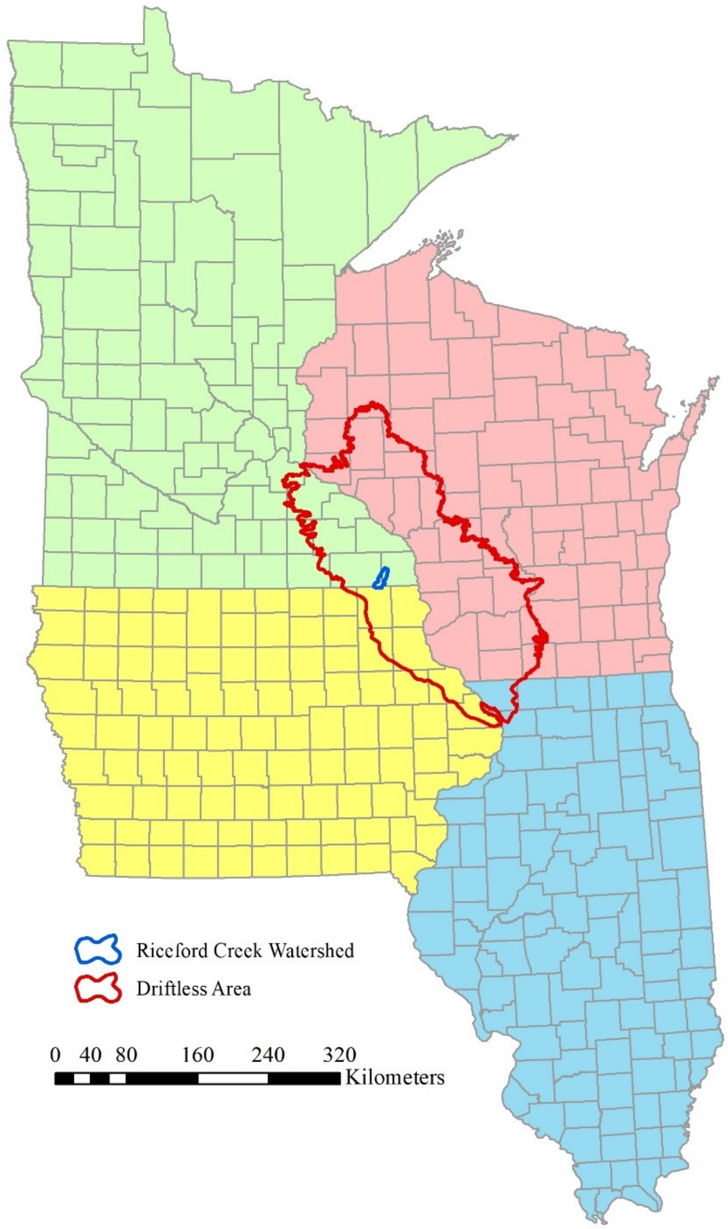


Figure 5. The Riceford Creek watershed is in the Driftless Area.

Figure 6. Early farming practices of plowing up and down steep slopes allowed runoff from the frequent and heavy rainfall in the Driftless Area to quickly erode loose soil and easily transport sediment directly to streams. Copy of photo is courtesy of Toby Dogwiler, source unknown.

Figure 7. sUAS imagery of Riceford Creek looking Southwest at the Lea Reach. This photo shows Riceford Creek is in one of the wide, incised river valleys filled with legacy sediment that are characteristic of the Driftless Area.

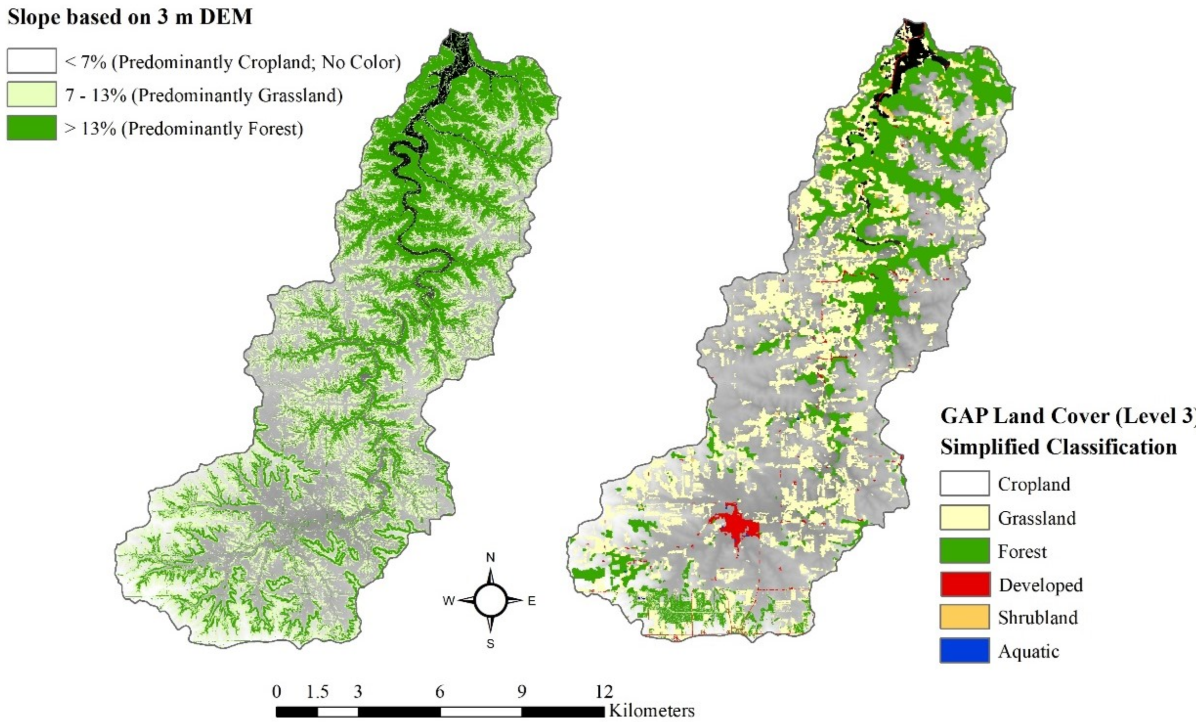


Figure 8. The relationship between slope and land use in the Riceford Creek watershed. Most of the watershed is used for cropland, with only the steepest slopes left as grassland and forest.

Figure 9. Cedars are harvested and lashed together end to end. Duck-Bill anchors are then used to anchor them to the base of eroding stream banks. The top photo was taken shortly after revetment installation. The bottom photo shows revetments after the needles have dried.

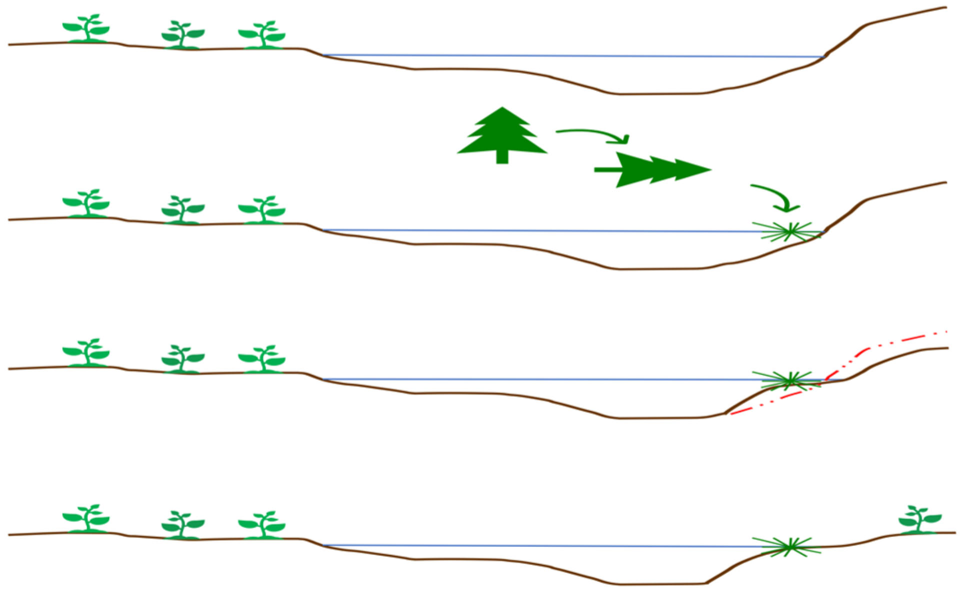


Figure 10. Hypothetic Diagram for a working cedar revetment. Cedars are anchored to the base of eroding banks. When the bank above the revetment collapses due to normal erosion, the sediment is caught in the branches of the cedar and the toe is stabilized, allowing material to collapse from the bank without bank retreat. Once the bank is shallow enough, grasses and other small vegetation grow on the bank and provide protection during subsequent erosive events.

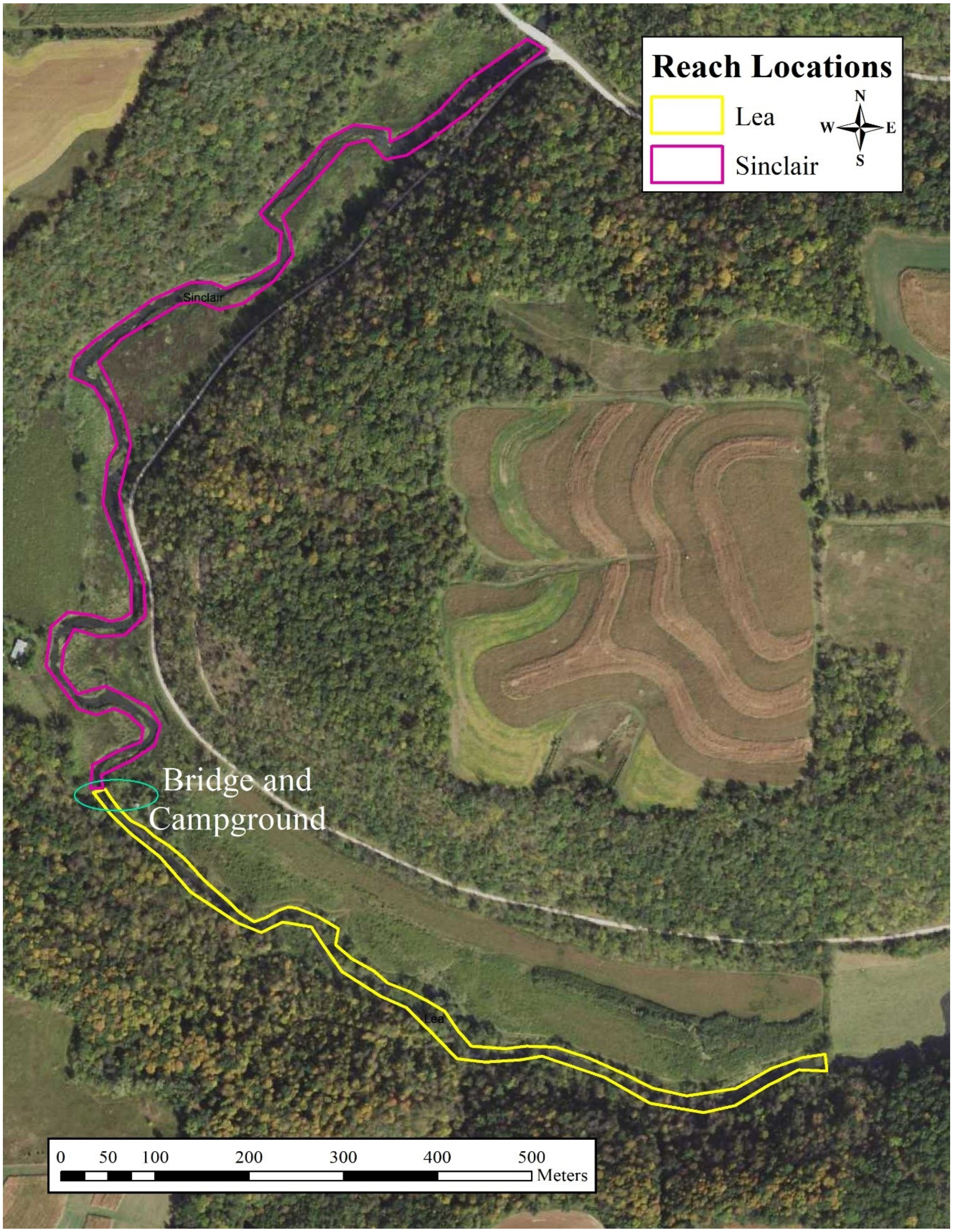
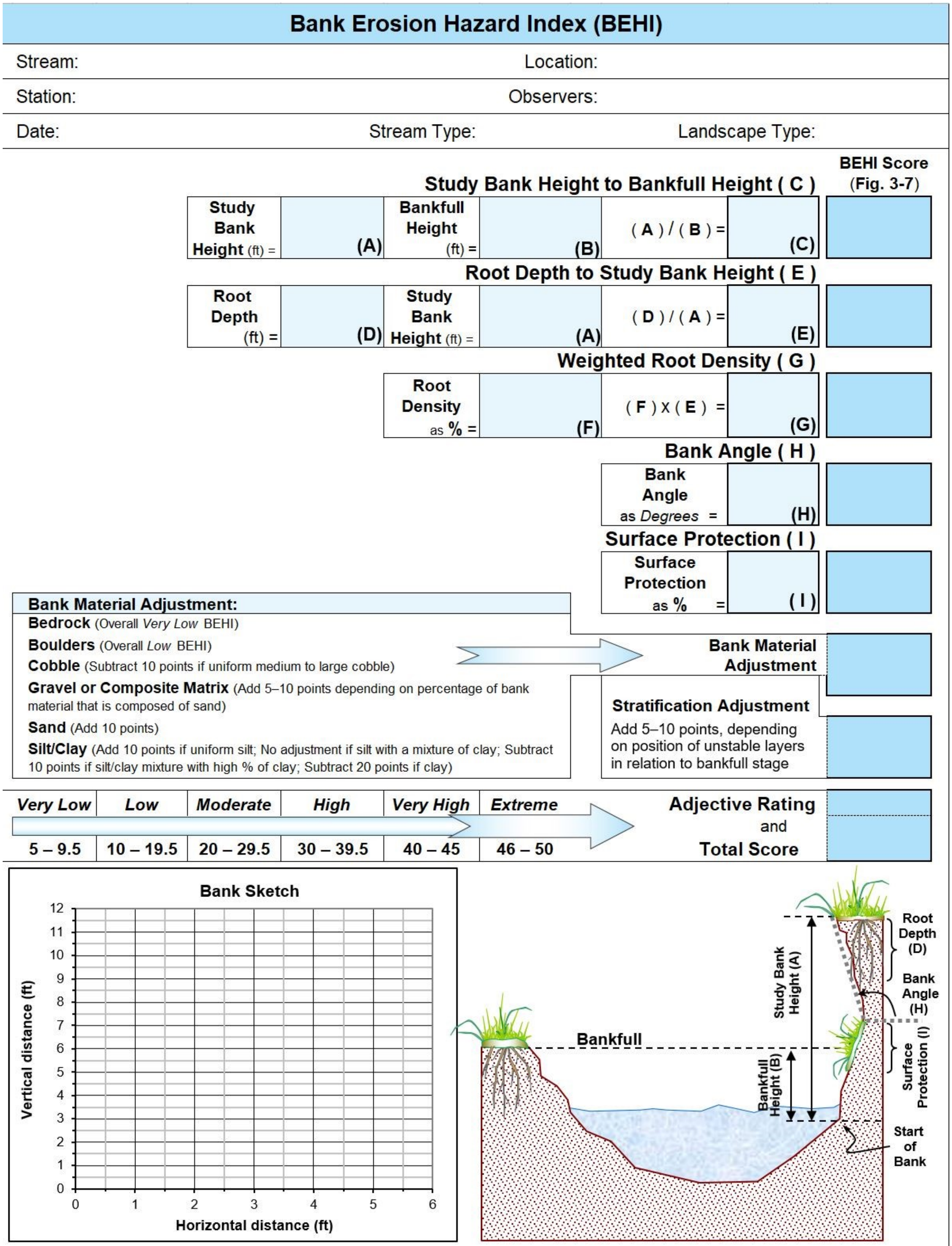


Figure 11. Lea and Sinclair Reaches with bridge and campground labeled.



Bank Erosion Hazard Index (BEHI)

Stream: Location:

Station: Observers:

Date: Stream Type: Landscape Type:

BEHI Score (Fig. 3-7)

Study Bank Height to Bankfull Height (C)

Study Bank Height (ft) = (A) Bankfull Height (ft) = (B) (A) / (B) = (C)

Root Depth to Study Bank Height (E)

Root Depth (ft) = (D) Study Bank Height (ft) = (A) (D) / (A) = (E)

Weighted Root Density (G)

Root Density as % = (F) (F) X (E) = (G)

Bank Angle (H)

Bank Angle as *Degrees* = (H)

Surface Protection (I)

Surface Protection as % = (I)

Bank Material Adjustment:

Bedrock (Overall *Very Low* BEHI)

Boulders (Overall *Low* BEHI)

Cobble (Subtract 10 points if uniform medium to large cobble)

Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)

Sand (Add 10 points)

Silt/Clay (Add 10 points if uniform silt; No adjustment if silt with a mixture of clay; Subtract 10 points if silt/clay mixture with high % of clay; Subtract 20 points if clay)

Bank Material Adjustment

Stratification Adjustment

Add 5–10 points, depending on position of unstable layers in relation to bankfull stage

Very Low	*Low*	*Moderate*	*High*	*Very High*	*Extreme*
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score

Figure 12. Spreadsheet with equations for determining BEHI scores (Rosgen, 2008).

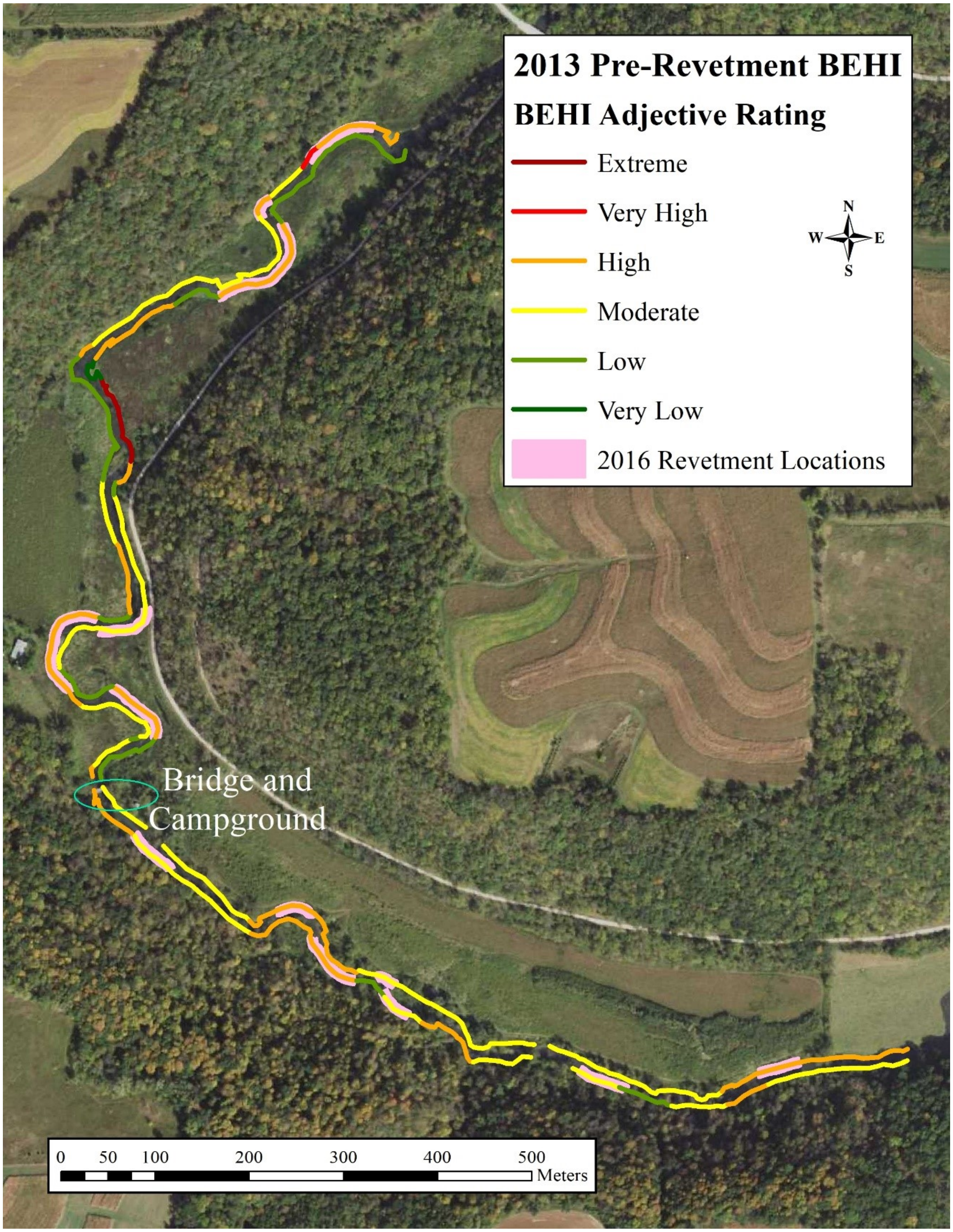


Figure 13. Pre-revetment BEHI classifications of Lea and Sinclair Reaches, Riceford Creek. The pink polygons indicate the stream banks where revetments were installed.

METHODS

Drone Imagery Collection

In the spring of 2016 and 2017 a sUAS was used to collect high resolution imagery of a 2.34 km section of Riceford Creek along the Lea and Sinclair reaches (Figures 14 and 15, respectively). Between these field seasons, in September 2016, a flood with an estimated 50-year occurrence interval inundated Riceford Creek. Flood waters rose at least several feet above bankfull in both the Lea and Sinclair reaches where imagery and stream data had been collected the prior spring. This provided the opportunity to evaluate how the revetments performed during the flood. Accordingly, in 2017 the focus was on collecting sUAS imagery and making detailed notes of the appearance of the banks along the entire stream. After collecting the initial imagery, a heavy snow storm made it impractical to continue collecting in-stream data that spring and a second trip was taken in early summer 2017. Based on both qualitative observations of Riceford Creek and quantitative assessment of stream gages along the Root River, there do not appear to have been any flows significant enough to cause channel modification between the September 2016 flood and the 2017 imagery and data collection. During the summer field season, stream flow data was collected and observations on where vegetation took hold on the banks were recorded.

The sUAS imagery was acquired using a DJI Phantom 3 Professional quadcopter with an integrated camera with 20 mm lens and 12.4 megapixel, 1/2.3” (1/5.8 cm) CMOS sensor. Both the 2016 and 2017 imagery were captured during leaf-off conditions in March. The image acquisition in 2016 was taken during a manual flight pattern along the stream valley. Figure 16

shows camera locations during the flight and indicates that there were at least 9 overlapping images in the river channel.

Photos were taken at altitudes ranging from 30 m to 120 m above ground level. The 2017 imagery was flown using a programmed flight plan with a flight pattern oriented roughly perpendicular to longitudinal valley orientation with flight altitudes 30 m to 60 m above ground level. Figure 17 shows that there is at least a 9 image overlap in the Lea reach, and a range of 3 to 9 overlapping images in the Sinclair reach. A goal of 2-4 cm nominal spatial resolution was used in planning the flights for both sets of imagery. In 2016 a total of 29 GCPs were laid out (orange, triangular, slow moving vehicle reflectors) and located using a sub-decimeter accuracy GPS. These were used as markers in the sUAS imagery. In 2017, seven GCPs were used (additional experience with the acquisition of sUAS imagery indicated that fewer GCPs were sufficient for the desired accuracy and results).

The imagery for each dataset was processed using Agisoft Photoscan software (v. 1.3x-1.4x). Photoscan was used to align the photos and then generate the dense point cloud, digital elevation model (DEM), and orthophotos. The initial georeferencing of the DEMs and orthophotos was accomplished in Photoscan based on the GCPs for each dataset. The DEMs and orthophotos were then exported to ArcGIS and their georeferencing was further refined by aligning identifiable fixed points, such as bridge and building corners and fences common to each set of imagery. The final aligned orthoimages for 2016 and 2017 are estimated to have a relative alignment accuracy of 5 to 15 cm (2016 had 2 cm average horizontal accuracy on GPS and 2017 had sub 2 cm horizontal accuracy on GPS). Based on visual inspection, accuracy of the aligned images was better than that in most areas. ArcGIS was used to manually digitize the stream banks for both years. Equidistant points along the digitized stream banks were then

generated and distance between stream banks from one year to the next was then calculated by doing a near analysis. Distances were assigned a negative value for all changes that occurred due to erosion and positive values for accretion. It was then necessary to digitize the locations of revetments as well as areas where revetments were washed out (Figures 18 and 19). With the revetment location data available in a digital format it was then possible to assign identifying numbers to each section of revetment and do a spatial join with the erosion/accretion data.

Joining the erosion/accretion data provides an association with specific locations where bank movement occurred, as well as whether cedar revetment was present. This also allows measurement of the length of stream bank for each criterion. The data was then exported to Microsoft Excel to calculate overall averages of bank change for each revetment site, as well as the non-revetted segments of the stream.

To calculate net erosion for each segment of the reach that had been given an initial BEHI rating in 2013, it was necessary to do a spatial join between the BEHI data and the erosion point data. Once the data was joined, it was exported into Microsoft Excel, and the average amount of erosion for each segment was calculated. A preliminary table was then created that included the stream segment, the BEHI adjective for that segment, and the average amount of erosion in that segment. From this table, average erosion for each BEHI category was calculated by combining the values under each BEHI adjective rating (Figures 20 and 21).

Stream Survey

Detailed hydraulic surveys of three reaches within a 280 m section of Riceford Creek in the Lea Reach were conducted in March 2016 (Fig. 22). The two downstream (north) reaches surveyed include banks with a cedar revetment treatment. The reach that is furthest south (and

upstream) is the control reach and did not receive a cedar revetment treatment. In 2017, cross-sectional data was collected in these three reaches and elsewhere in the Lea reach including several areas where cross-sections had been collected in both 2013 and 2014 (Fig. 23). Data on bank angle, slope distance, and stream velocity, was collected along the downstream right bank in the Sinclair Reach at revetment 8 (called Sinclair 1 in Figure 23). Observations were also made on revetment and vegetation conditions at all sites. Revetment 13 was also observed, and notes were taken on revetment conditions, vegetation, and the presence of a lateral bar (sediment shelf) that formed under the intact revetments. This sediment shelf was absent where revetments were washed out.

In 2013 and 2014 cross-sections of Riceford Creek were collected using an Auto Level and a tape. Some of the cross-sections were duplicated in 2016 and 2017 by locating the GPS positions of the ends. Because of the error inherent in re-occupying a location based on a GPS (without a monument or flag) the 2016 and 2017 cross-sections were not precisely co-located. Based on the accuracy of the GPS we estimate an accuracy of within 20-50 cm. The locations chosen for the cross-sections had generally uniform morphology within this error range and we believe the data yield a reasonable comparison of the changes between 2016 and 2017. The 2016 stream survey data was collected using a Trimble Geo7x centimeter accuracy GPS for x- and y-coordinates and a rotary laser for z-coordinates (i.e., elevations). The GPS data was post-processed to 1 to 10 cm accuracy using a nearby Minnesota Department of Transportation CORS base station. The 2017 cross-section data was collected using a theodolite. The location of the theodolite was recorded with a GPS and then the UTM coordinates of each side shot from the theodolite were calculated based on the theodolite’s absolute coordinates.

The 2017 theodolite-based survey was verified by overlaying it in ArcMap on the 2017 sUAS-acquired orthorectified photo. This, in conjunction with field notes and photographs, allowed any positional errors due to the GPS accuracy or the surveying of points to be correctly transformed to their true positions relative to the stream bank (see Figures 24 and 25). For each of the cross-sectional surveys the points were moved as groups and not as individual points—that is they were shifted or rotated in the x-y plane. After this correction, the point locations were exported with the corrected northing and easting coordinates for further analysis.

Graphs for each cross-section were created using Microsoft Excel. Data from each year were first graphed with the raw data, and then transformed to more closely align end points, bank features, and/or water levels with data collected during other years. This took the form of adding or subtracting several meters in elevation for one or more years, as well as adding or subtracting "distance on tape" where appropriate.

Velocity

Water velocity was collected using a model 3000 Swiffometer velocity flow meter. Data was collected at 60% water depth, averaging velocity for 1 minute. In 2016 velocity was collected at every point marked by GPS during the stream survey (Fig. 26). These include points midstream, near bank, near cedars, and in the cedar revetments. In 2017 velocity was only collected at 5 points across the stream at cross-sections 89, 8 and 88. Velocities were also collected outside (toward midstream) the cedar revetments (or where revetments would have reached if they were not in place) and among the branches of the cedar revetments (or where they would have been) at several locations upstream and downstream of cross-sections 89, 6, 8, 88, and Sinclair 1 (Fig. 27).

Spatial Analysis of Stream Velocity

A Point Pattern Analysis can determine if there is significance in the spatial variation in values of point events (e.g., are values randomly distributed, or is there a pattern due to some process) (Gatrell, A.C., Bailey, T.C., Diggle, P.J., and Rowlingson, B.S., 1996). Getis Ord Hot Spot Analysis and Local Moran's I Cluster and Outlier Analysis were used to determine if the difference in near bank velocity in revetted reaches of the stream and non-revetted reaches was significant. Local Moran's I distinguishes between point values that are clustered and point values that are randomly distributed by looking at a points value (e.g., velocity) and testing it against its neighbors as well as the rest of the study area. If the values are more similar (or dissimilar) than would be expected in a random distribution, they are clustered. Local Moran's I is able to distinguish between high-value clusters and low-value clusters, as well as distinguishing outliers within those clusters (Getis and Ord, 1992; Mitchell, 2005; Ord and Getis, 1995). Getis Ord is able to test for clustering by similarly comparing neighboring values (and study area values), as well as distinguishing between high- and low-value clusters and spatial associations. However, Getis Ord does not identify outliers within clusters (Getis and Ord, 1992; Ord and Getis, 1995).

Because velocity data for Riceford Creek was collected in clusters over a large area, the first step of running the analysis was to divide the data into sub-reaches. Since the 2016 data points were associated with dGPS locations the X-Y data was imported directly into ArcGIS and a shapefile was created. In ArcGIS, the polygon select tool was used to group points into sub-reaches and create separate shapefiles for each sub-reach (Fig. 26). The Getis Ord and Local Morans I spatial analysis tools were then run on each sub-reach to analyze the spatial patterns in the velocity data.

Since the 2017 velocities do not have GPS locations associated with them, each point was first assigned an identifying number. Then ArcCatalog was used to create a blank point shapefile. Points where velocity measurements were taken were then hand-plotted in ArcMap using the field notes, pictures taken during the field work, and sUAS imagery as references. A spatial join of the shapefile to the Excel spreadsheet was then performed. Separate shapfiles were then created for each subreach (Fig. 27), and then Getis Ord and Local Morans I tools were run on each of those shapefiles.

Getis Ord and Local Morans I need at least 30 sample points for the analysis to produce meaningful results. Having fewer points can skew the results. All 3 reaches of the 2016 data have over 30 points, so this is not an issue for those analyses. However, the 2017 data have between 8 and 15 points per reach. Because of the small sample size of the data, the results for 2017 are not statistically sound and are not included.

Figure 14. sUAS imagery 2016

Figure 15. sUAS imagery 2017

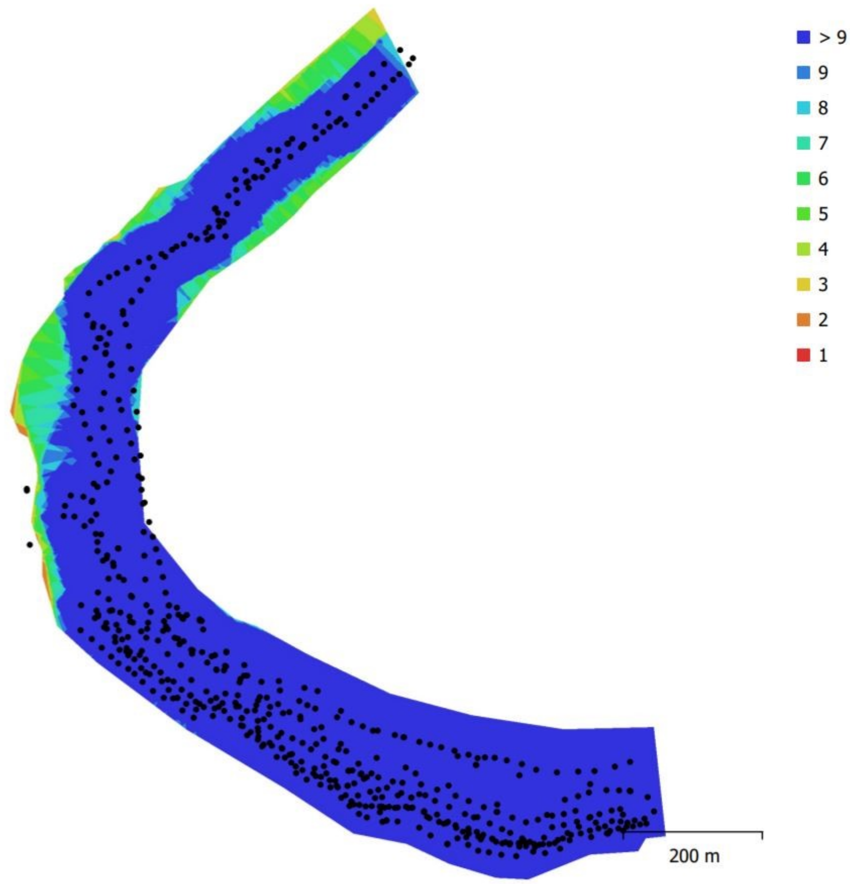


Figure 16. Camera Locations and photo overlap from 2016 sUAS imagery acquisition.

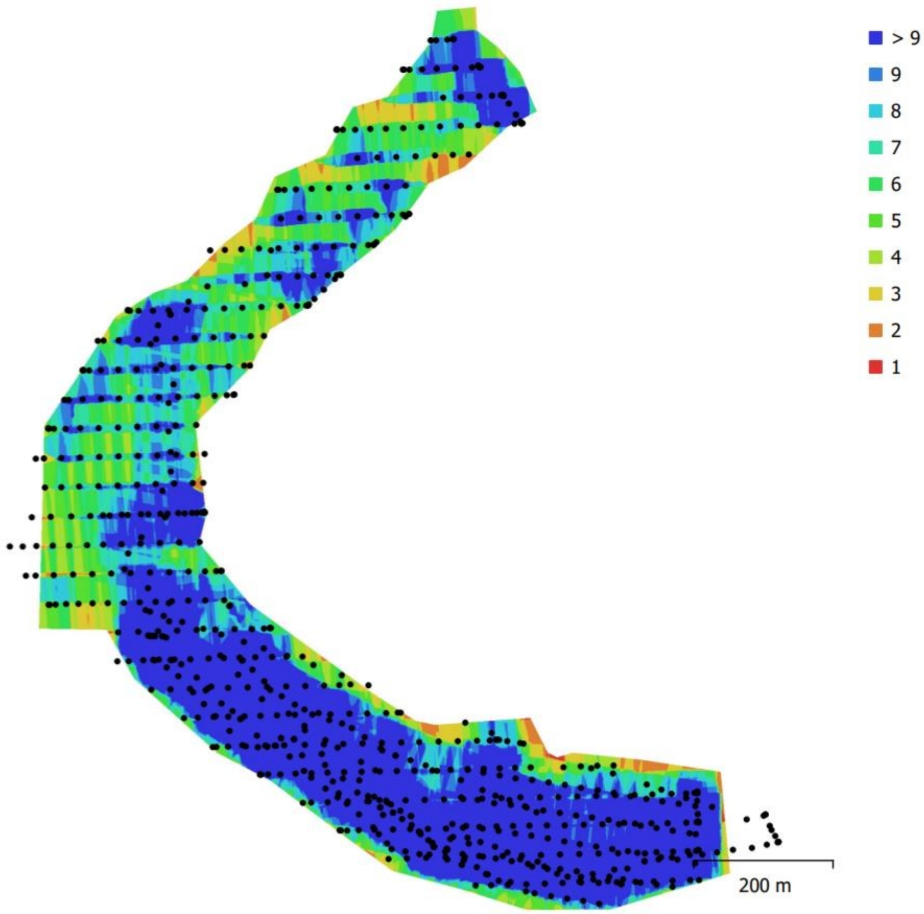


Figure 17. Camera Locations and photo overlap from 2017 sUAS imagery acquisition.

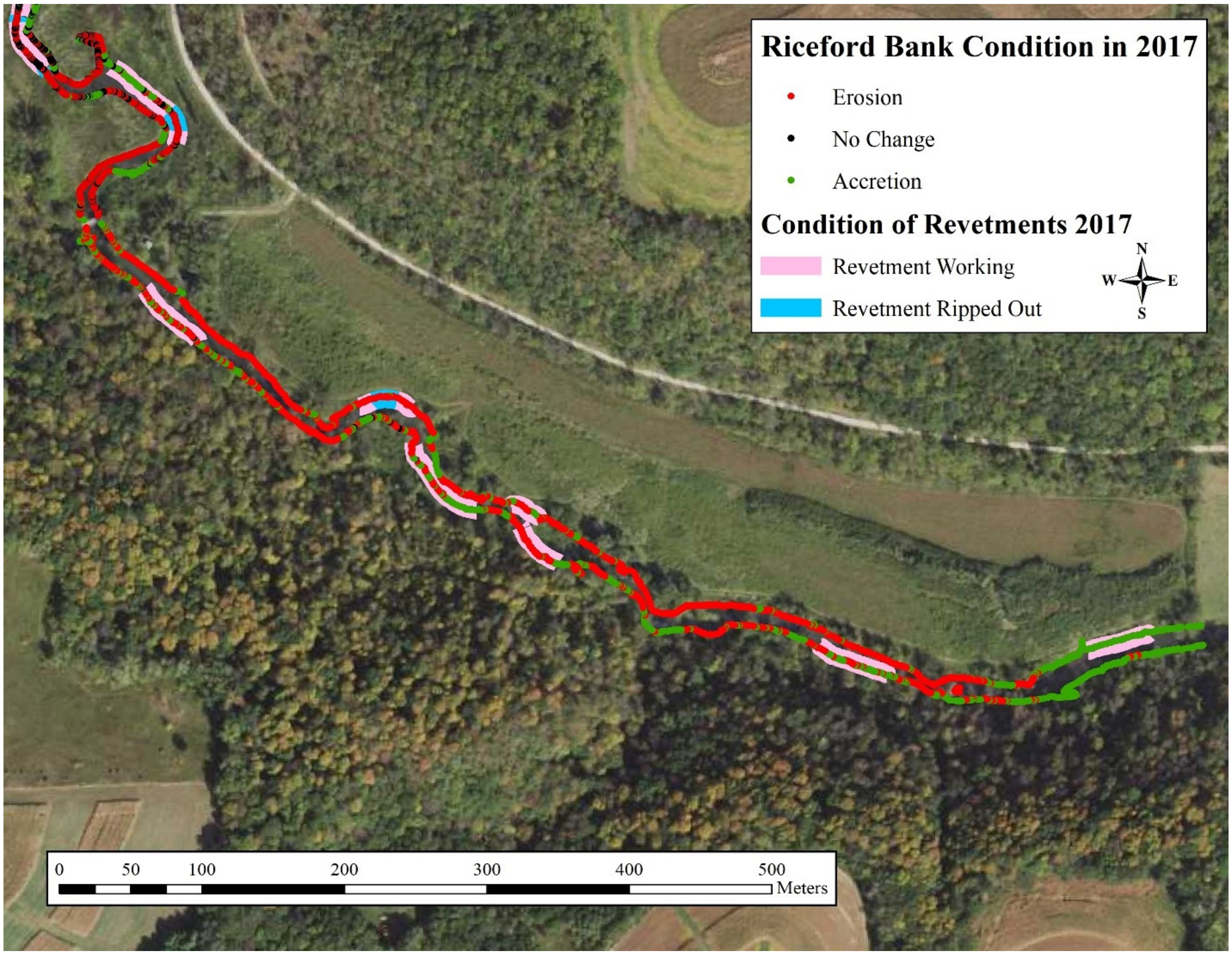


Figure 18. Change in channel position from 2016 to 2017 in the Lea Reach. Red indicates areas where the bank retreated away from the thalweg (i.e., eroded) and green indicates areas where the bank accreted (i.e., deposition in the channel). Black dots are areas of no change.

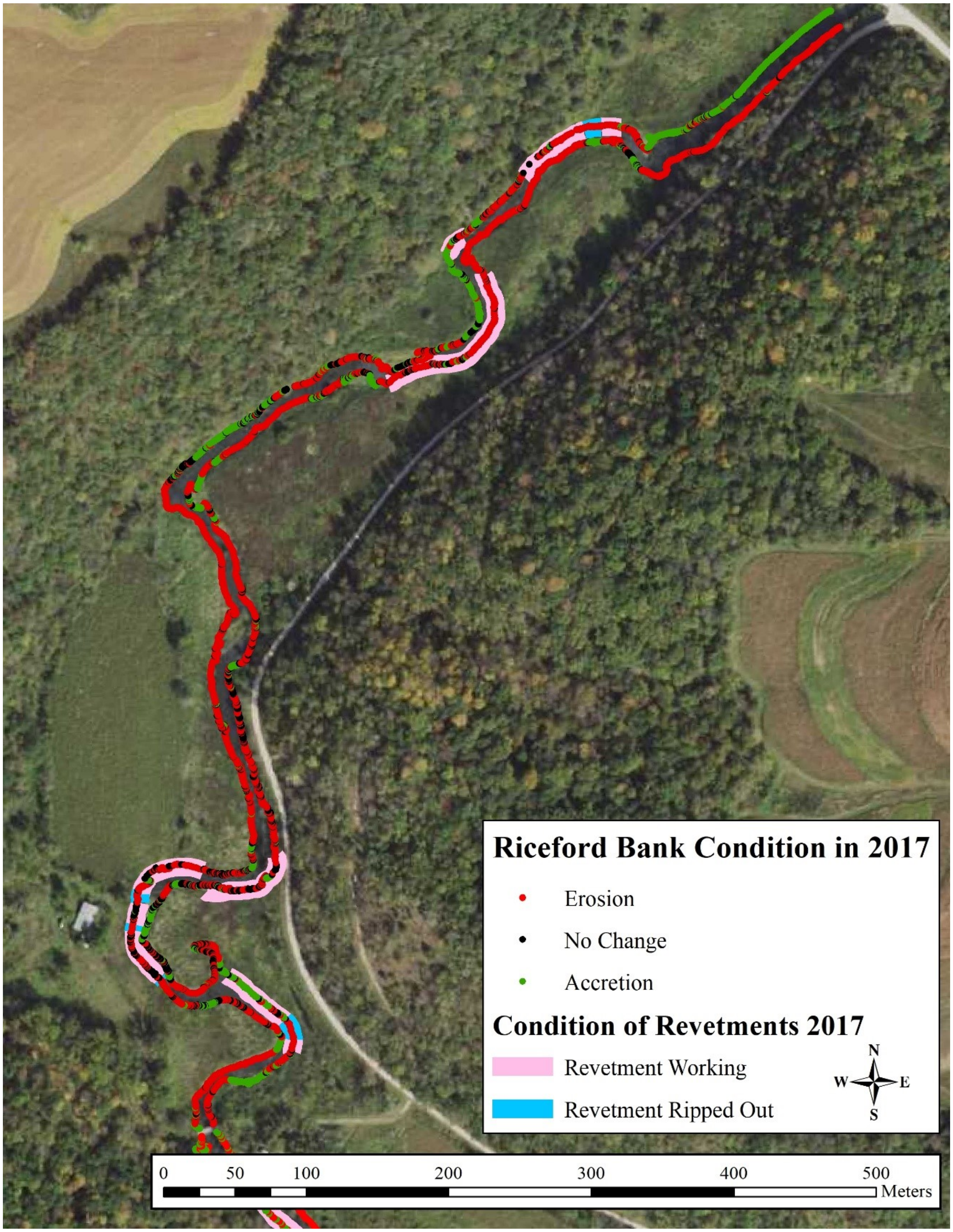


Figure 19. Change in channel position from 2016 to 2017 in the Sinclair Reach. Red indicates areas where the bank retreated away from the thalweg (i.e., eroded) and green indicates areas where the bank accreted (i.e., deposition in the channel). Black dots are areas of no change.

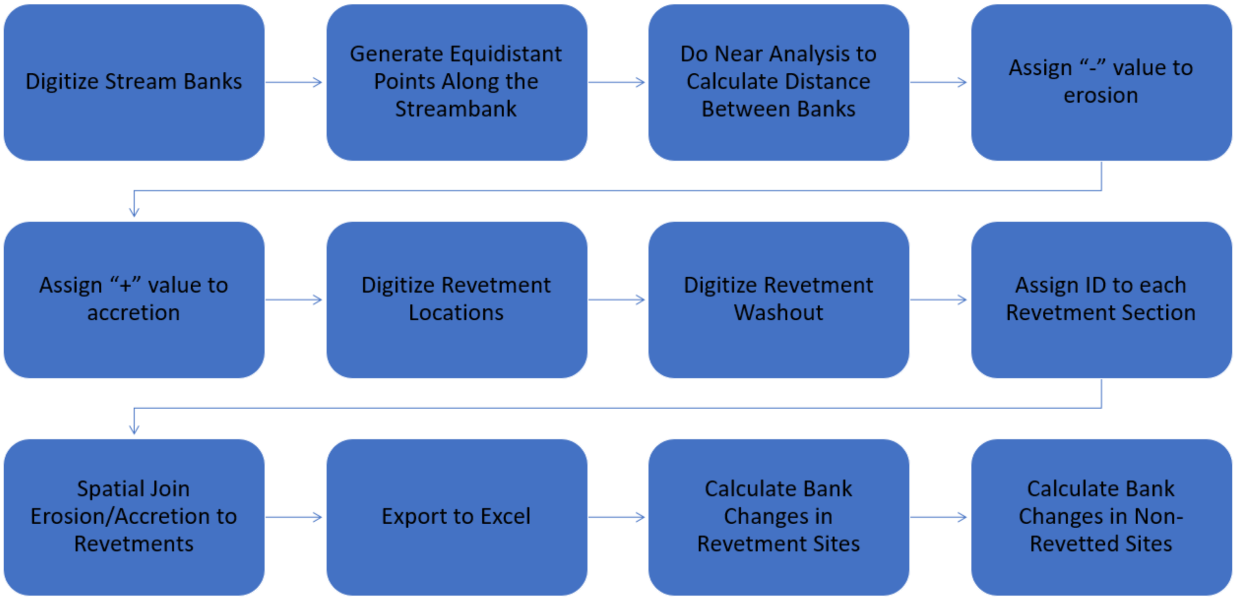


Figure 20. Workflow for calculating erosion based on revetment location and status.

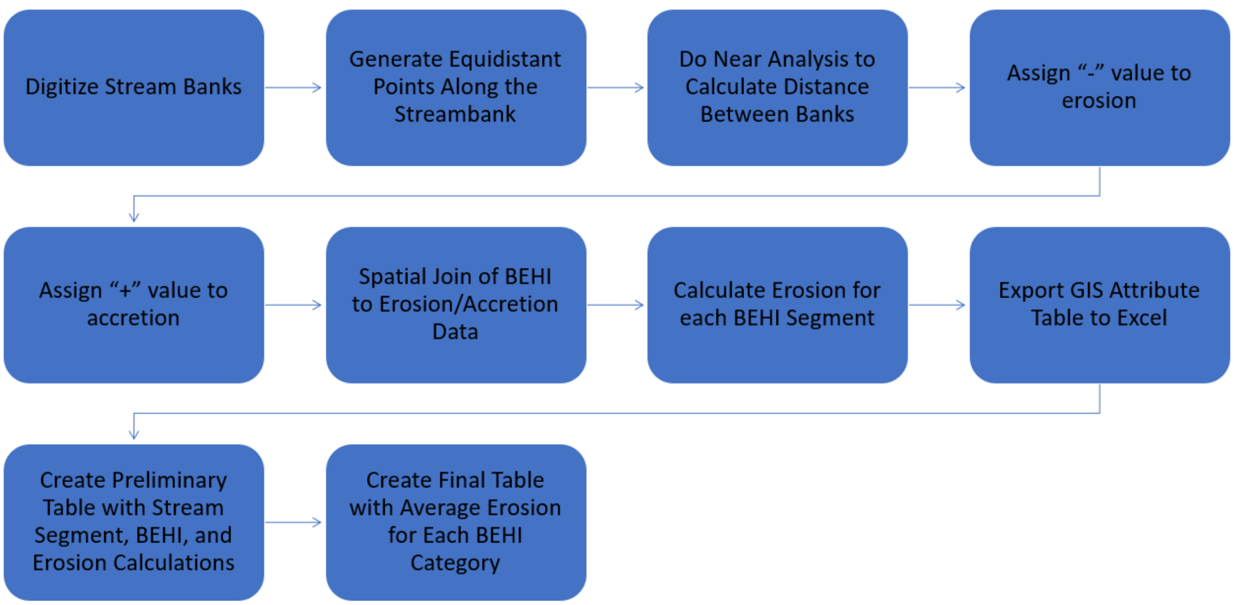


Figure 21. Workflow for calculating erosion based on BEHI scores.

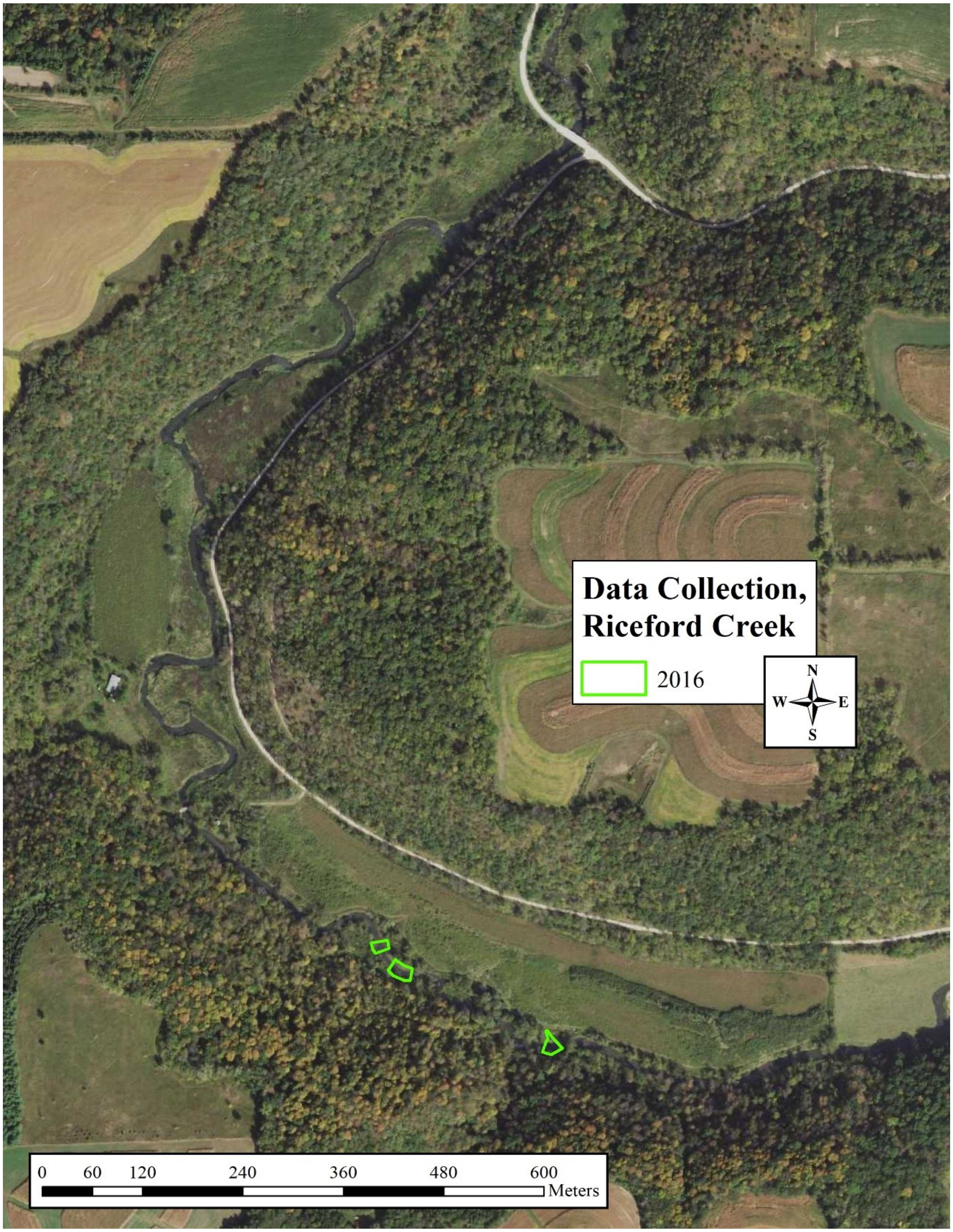


Figure 22. Locations of the 2016 stream surveys in Lea Reach.

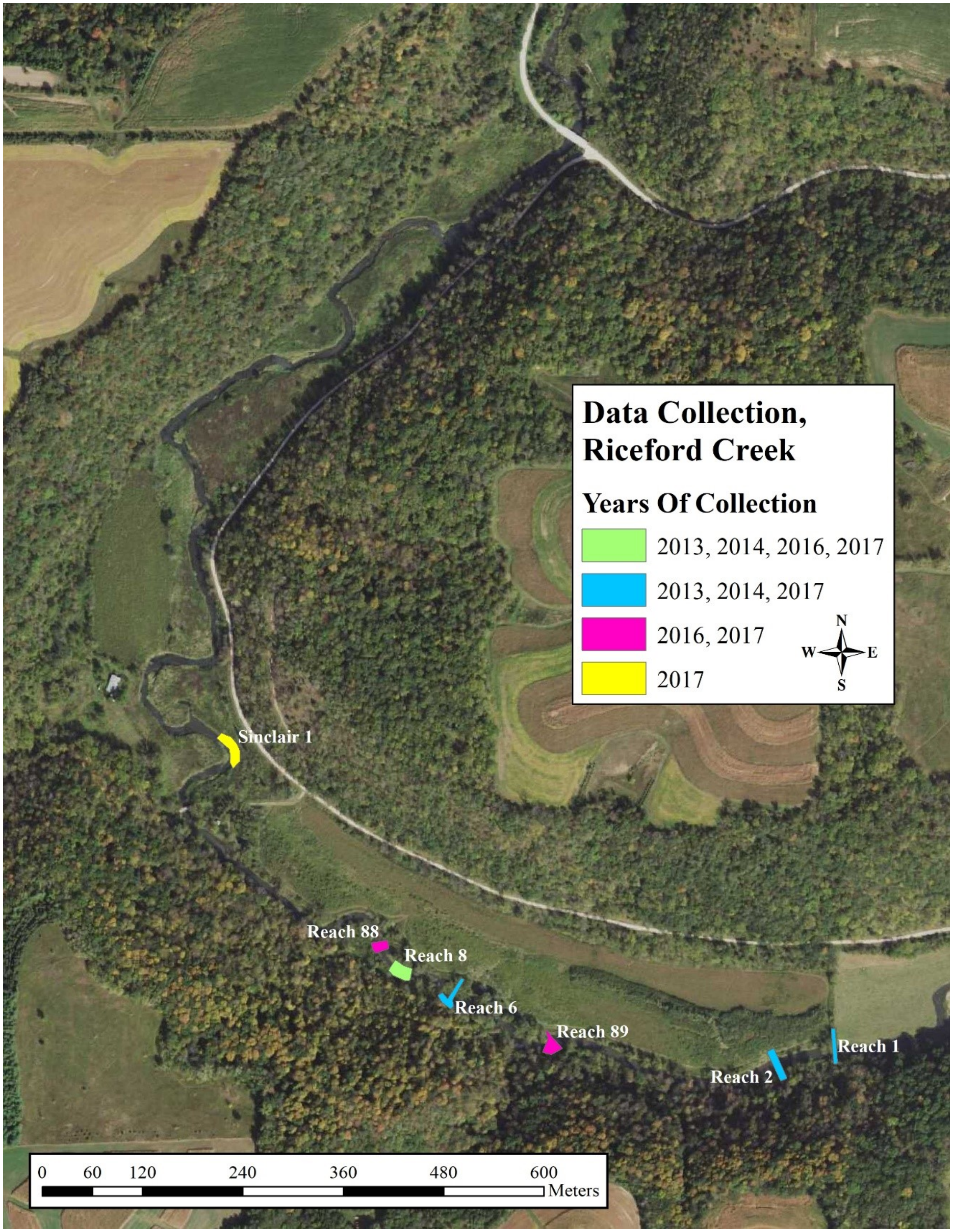


Figure 23. Locations of 2017 Stream Surveys showing the 5 areas where velocity and other data were collected in the Lea and Sinclair reaches, with 2013/14 data overlay (each color indicates what years data was collected). The stream flows from right to left in this image, and from South to North.

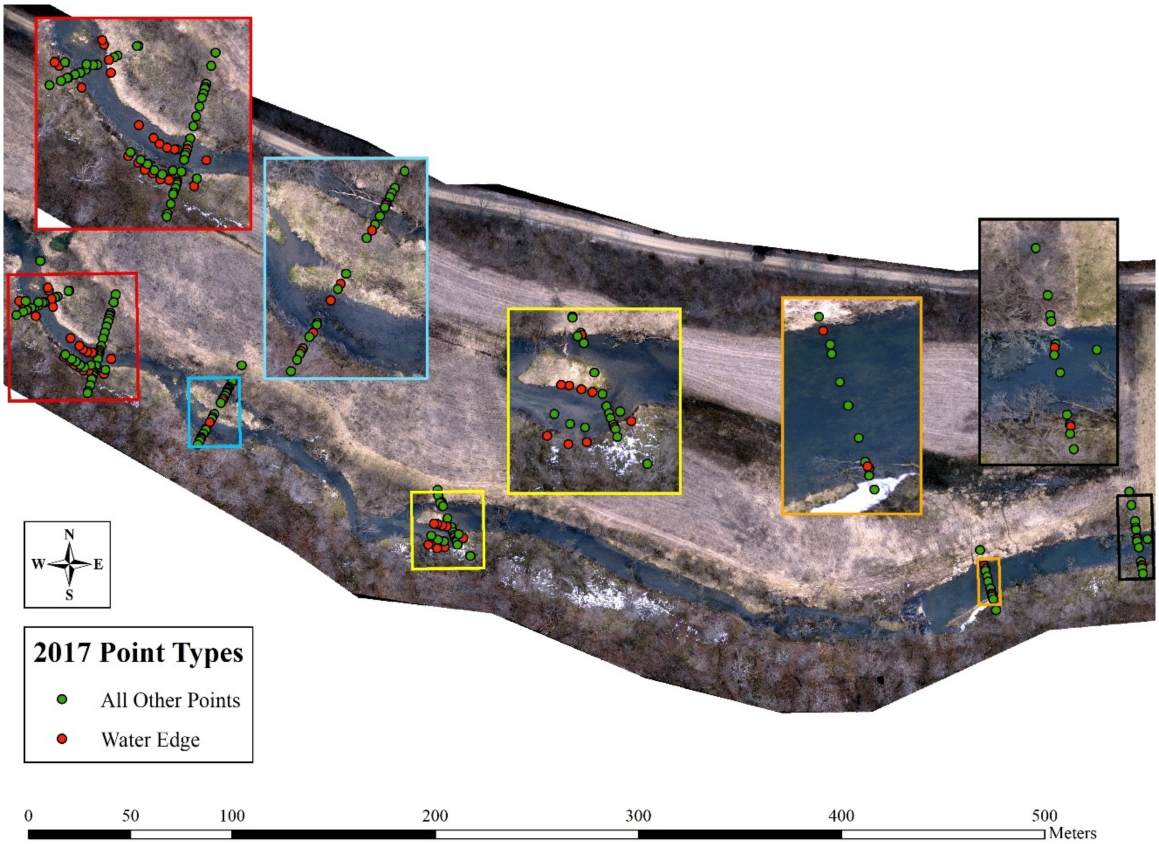


Figure 24. 2017 data in Lea, before it was corrected to align with the imagery.

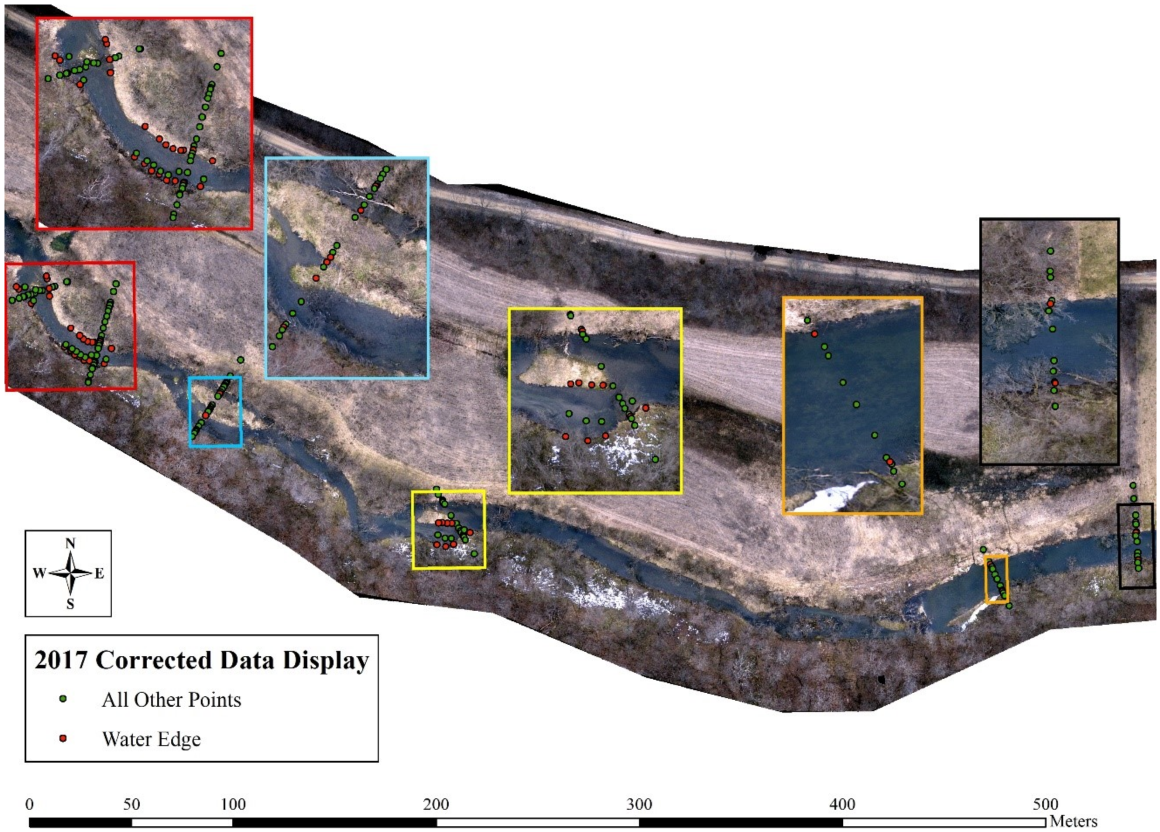


Figure 25. 2017 data in Lea after corrections were applied to align the data with the imagery.

Figure 26. GPS points from the 2016 stream survey of the Lea Reach in Riceford Creek divided into subreaches. Velocity was collected at every point in the channel.

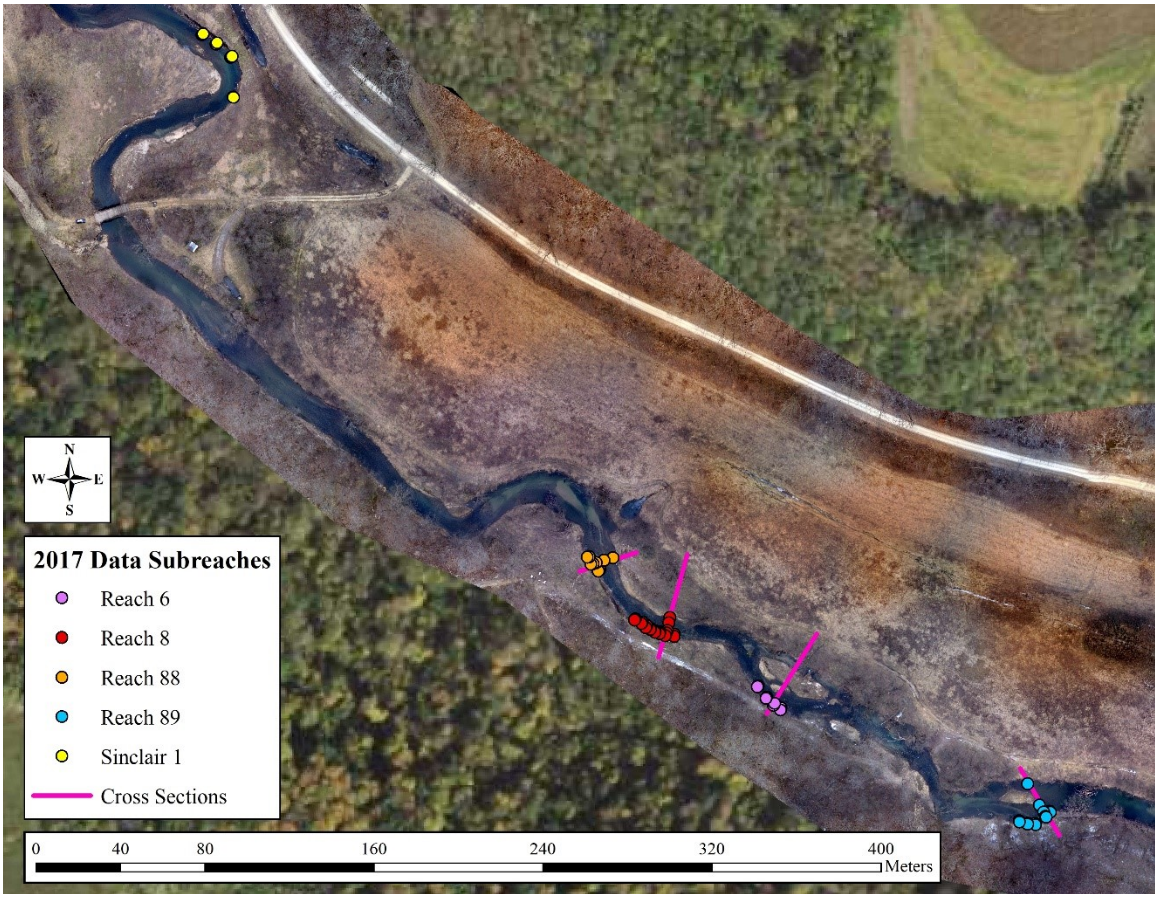


Figure 27. Points where velocity was measured during the 2017 stream survey of the Lea and Sinclair Reaches in Riceford Creek divided into subreaches.

RESULTS AND DISCUSSION

Drone Imagery Analysis

The sUAS imagery collected in 2016 and 2017 has a horizontal resolution of 3-5 cm and the stream feature digitization based on that orthophoto has an estimated accuracy of ± 0.1 m. As such, any changes detected between the 2016 and 2017 imagery that are greater than about 0.1 m are discernible and can be quantified within those error limits.

During field work in 2016 it was noted that there was a beaver dam just downstream of cross-section 2 (Fig. 28). The dam did not exist in 2013/2014 when the stream bank prioritization and revetment installation occurred. The beaver dam created a pool that extended upstream approximately 180 m and completely submerged revetment 1 (Fig. 29).

In 2017, the beaver dam was gone (presumably washed out by the September 2016 flood), and upstream water levels had dropped and exposed the revetment. Observations and calculations suggest that the beaver dam resulted in higher sedimentation and lower erosion upstream of the dam than were seen in downstream reaches. While these are favorable results, the beaver dam was not part of the plans or design to study the effect of revetments on stream bank stability and any effect—positive or negative—would be difficult to intentionally reproduce. Accordingly, the data from revetment 1 and the stream banks within the upstream influence of the beaver dam will not be further considered in the results or discussion.

Preliminary analysis shows average lateral erosion for the combined Lea and Sinclair reaches of Riceford Creek from 2016 to 2017 as a net loss of 0.30 m over 4,191 m of stream banks. Most of the study area (82%) is un-revetted with average erosion of 0.31 m. The portion of the study area that was treated with revetments (18%) had an average erosion of 0.25 m (Table

1). These results show that during a 50-year flood, more erosion occurred in areas that had not been revetted than in areas that were treated with a cedar revetment.

An analysis of how well each revetment performed individually during the flood reveals that while some of the revetments had portions of the revetment washed out (which will be referred to as “damaged”), none of the revetments were completely washed out. Revetment 5 performed best with an average of 0.22 m of accretion (Table 2). The next best performing revetment was Revetment 12 with 0.13 m of accretion. Erosion rates for each revetment in Table 2 were first calculated based on where revetments were originally installed in 2013/2014 (ignoring the fact that some revetments were damaged by being partially washed out). Results show revetments that were damaged generally had more erosion than revetments that stayed intact. The two exceptions are Revetment 3 and Revetment 11.

Calculating erosion by splitting the revetments into “intact” and “damaged” portions yields lower net erosion in the intact portions. For example, revetment 8 as a whole has a net loss, whereas looking at just the intact portion shows a net gain of 0.09 m. When only calculating erosion for intact revetments, 3 of the revetments resulted in net accretion after a 50-year flood and 3 of the revetments resulted in less than 5 cm of erosion. Most of the revetments that were damaged had more erosion than the entirely intact revetments. This is expected since the fact that areas of those revetments washed out would indicate they were subject to highly erosive forces.

Table 3 compares how much erosion occurred in areas where revetment stayed intact versus areas where revetment was damaged. Of the 771 m of revetments that were placed, only 61 m (or 7.9% of revetments) were damaged during the 2016 flood. The majority (92.1%) of revetments that were installed successfully stayed intact during a high-flow event and resulted in an average of 0.19 m of erosion. Areas where revetment was damaged had 0.98 m of erosion.

Including erosion calculations where revetments were damaged in the “revetments installed” calculations (see Table 1) can make it appear that in-place revetments were subject to more erosion than they sustained. The measurements are left combined in Table 1 because of the fact that since the revetment was damaged and did not prevent erosion as effectively it could still be considered a failure of the technique. This reveals two things: 1) where cedar revetments stayed intact, they made a visual and measurable difference in stabilizing the stream banks and 2) the areas where cedar revetments were damaged were highly susceptible to erosion. This indicates that either cedar revetment is not appropriate for some types of banks or the stream banks hadn’t sufficiently stabilized (i.e. healed) in the amount of time between installation and the flood. It is possible that if the flood had not occurred for a few more years (or if it had been smaller in magnitude) those sections would have stayed intact and the amount of erosion in those areas would be lower. This is currently an open question that the data cannot answer. The damaged revetments are all in areas that were given a “High” BEHI rating. This suggests that the BEHI method is generally a good technique for evaluating hazard areas and prioritizing placing revetments in streams.

Table 4 summarizes the average erosion according to the original BEHI adjective rating that was determined along Riceford Creek. Comparing average erosion for “Intact” and “Damaged” portions of the revetments reveals how the “High” BEHI class is skewed by the presence of damaged revetments in that class. As would be expected when looking at “Total Average Erosion,” the most erosion (0.86 m) occurred in the “Extreme” BEHI class. Going down from there are “Low” with 0.44 m, “Very Low” with 0.27 m, then “Moderate” and “High” both with 0.28 m of erosion. The least net erosion occurred in the “Very High” class and has a net accretion of 0.04 m.

Evaluating only the revetted portions of each BEHI class shows that all revetments in the “Very High” BEHI class stayed intact during the flood and resulted in a net accretion of 0.19 m. (Table 4). This revetted section is 17 m long, and is on the upstream end of Revetment 13, on a straight stretch of the river. The next best performing revetments were in the “Moderate” BEHI class, with 0.09 m of erosion. The “High” BEHI revetments follow with 0.24 m of erosion. The “Low” revetments had the most erosion with 0.47 m. Interestingly, this calculation for the “Low” BEHI is heavily effected by interpretation of the sUAS imagery of an approximately 3 m section (21% of the revetted stream bank length in the “Low” BEHI category) at the downstream end of Revetment 3.

In the 2016 imagery, there is visible cedar revetment in this section but in 2017 it is harder to see. After looking at individual sUAS photos it was determined that the revetment is still in place, but this was not evident in the 2017 orthophoto. This section is adjacent to (downstream of) a bank that received a “Moderate” BEHI score, and these 3 meters may have been misclassified either during the original survey, or when the results were mapped. The BEHI score was mapped using imagery with low resolution and vegetation covering the stream banks. It is these 3 meters of revetment that explain the placement of Revetment 3 being so low in Table 2. When this section is left out of the calculations, Revetment 3 has 0.27 m of erosion in the intact revetments and 1.60 m of erosion in damaged revetments. It also results in “Low” BEHI revetments having only 0.22 m of erosion.

Comparing average erosion between un-revetted areas and revetted (and intact) areas results in three of the calculations showing greatly reduced erosion in areas with revetment, with an average difference of 0.27 m. However, the “High” BEHI class shows no difference between

areas that were revetted and where the revetment stayed intact. This is within the ± 0.1 m error range for the data and is seen as being consistent with the overall trends of revetment success.

Overall, Table 4 gives mixed results on the correlation between BEHI and erosion. The "Very High" and "Low" BEHI have limited sample sizes of revetted stream bank. "High" shows no difference between erosion in revetted versus un-revetted reaches unless you look at the damaged portion. The "Moderate" BEHI is the only category that shows significantly less erosion in the revetted stream reaches (as compared to the erosion in the un-revetted portions).

Because Table 4 suggests that the individual BEHI ratings were not useful for prioritizing or predicting revetment success an additional analysis was performed with the BEHI ratings combined into two broader groups. Table 5 provides the same data as Table 4 with the BEHI adjective ratings combined into the two groups (as well as the reaches where no BEHI ratings were determined). This table shows that the "Extreme to High" reaches received the highest percentage of revetment compared to length of rated stream bank (42%). This group experienced the same overall erosion when un-revetted and revetted reaches are compared (0.31 m). However, a comparison of the average erosion of the intact versus the damaged revetments reveals that the average erosion for the revetted reaches is skewed upward by the relatively high erosion that occurred in areas with damaged revetments. The intact revetments successfully reduced the erosion to 0.23 m, which is a 26% reduction relative to the erosion in the un-revetted reaches. For the "Moderate to Very Low BEHI" reaches there were no damaged revetments. In these reaches the revetments decreased erosion to 0.11 m, which is a 69% reduction, as compared to the 0.35 m of erosion in the un-revetted sections.

An argument can be made that once the revetments in the "Extreme to High" reaches were damaged those areas became un-revetted and should be reclassified as such. Table 5a

provides an analysis with the damaged revetments combined with the un-revetted reaches and then compared to the intact revetments. This shows that the un-revetted and damaged revetted reaches averaged 0.36 m of erosion compared to 0.23 m in the intact revetments, which is a reduction of 36%. Once this reclassification is taken into account, there is no significant difference in erosion between the un-revetted (and damaged revetments) reaches classified “Extreme to High” and “Moderate to Very Low”. However, the revetments in the “Moderate to Very Low” reaches were more effective (69% vs. 36%) indicating that the shear stresses along the banks were lower than in the “Extreme to High” reaches. This is further supported by the observation that the erosion in the damaged reaches was 0.98 m, which is about 4 times the erosion of the intact revetments. Finally, it is worth noting that only 61 m (8%) of revetments failed out of a total of 771 m of treated stream bank. This indicates that the revetment techniques were largely successful in terms of surviving the flood and reducing the overall erosion. This also suggests that the broader BEHI grouping approach (“Extreme to High” and “Moderate to Very Low”) did provide a useful means of prioritizing stream reaches for revetment installation.

Stream Survey

Cross-sections of the stream channel within the study reaches were created from data collected in 2013, 2014, 2016 and 2017. Locations of cross-sections in the creek are shown in Figure 28. Cross-sections 1 and 2 have data from 2013, 2014, and 2017. Cross-section 1 is in a non-revetted section of the stream and stream width appears to have increased by about 2 m from 2013 to 2017 (Fig. 30 and Table 6).

The bank slope on the (facing downstream) left bank (DSL) increased each year becoming about 15-20^{o} steeper by 2017, while the slope on the (facing downstream) right bank

(DSR) first decreased in steepness from 2013 to 2014, and then increased slightly in 2017 for a total slope change of about 15º shallower from 2013 to 2017. Cross-section 2 had revetments placed on the DSR bank before data collection in 2014 and shows bank width increasing by about 2.5 m from 2013 to 2017 (Fig. 31 and Table 7).

The slope on the un-revetted DSL bank got steeper by about 5-10º while the revetted bank got shallower by 20-30º. Both cross-section 1 and 2 are upstream of a beaver dam that was built in the Lea Reach between 2014 and 2016. The dam was then washed out before data collection in 2017 (Figures 28 and 29), presumably due to the September 2016 flood. It is unknown if the beaver dam had an influence on these cross-sections and if it did, how significant that influence was. The cross-section for Line 89 skirts the upstream edge of a vegetated medial gravel bar close to the DSR bank. This is a non-revetted reach and only has data from 2016 and 2017 (Fig. 32 and Table 8). While the entire stream width did not change a measurable amount, the DSL bank of the medial gravel bar appears to have eroded about 1.5 m, indicating that there was significant flow between 2016 and 2017. The DSL bank slope appears to have decreased by about 30-40º while the DSR bank slope became around 30º steeper.

Cross-section 6 was surveyed in 2013, 2014, and 2017 and includes a large vegetated medial gravel bar (Fig. 33). The DSL bank was revetted between the 2013 and 2014 surveys. Based on comparison of the cross-section surveys the location of the revetted DSL bank has been stable while the slope angle is getting slightly less steep in each survey (Fig. 34). The revetment just upstream of the cross-section performed very well. In 2017 it was almost entirely incorporated into the stream bank with just a few branches from the cedar trees sticking out above the soil. The revetment was approximately half a meter inland from the water's edge. The bank behind the revetments was also less steep than the surrounding banks (Fig. 33).

Presumably, as the initially steep bank slumped, the cedar branches in the revetment were able to hold onto the slumping sediments thereby providing a stable toe to the bank. Conversely, the overall channel width, medial gravel bar width, and the DSR banks all changed between 2013 and 2017.

Between 2013 and 2014 the island width appears to have narrowed by around 0.5 m and the water channel on the DSL side of the medial island narrowed by about 4 m. This appears to represent the growth of another small gravel bar on the DSL side of the main medial bar (Fig. 33). The overall channel width also decreased by about 1 m. By 2017 the water channel had widened by about 2 m mostly as a result the retreat of the DSR bank. The DSL bank was also about 5˚ shallower (Fig. 34 and Table 9). All of this suggests that the DSL revetment did a good job of stabilizing the DSL bank over this period but that various flows, including the large 2016 flood, continued to work the DSR bank. In 2017, the DSR bank was significantly less steep (by about 30-50˚) than in the earlier surveys. The now shallower slope on the DSR bank may reduce the rate of slumping and foster vegetation growth which could help stabilize it in the future.

Cross-section 8 was surveyed in 2013, 2014, 2016, and 2017 and received revetment treatment on the DSL bank before the 2014 survey (Fig. 35 and Table 10). Bank width decreased each year with a total decrease of about 1 m from 2013 to 2017. The graph from 2017 shows how the top of the DSL bank stepped back while the toe stayed stationary, effectively making the bank shallower and providing a slope that vegetation can take root on. The revetted DSL became shallower by about 30º while the non-revetted DSR slope became steeper by about 5º.

Cross-section 88 was also revetted on the DSL bank and was surveyed in 2016 and 2017 (Fig. 36 and Table 11). This reach decreased in width by about 1 m while also decreasing bank slope on both banks. The revetted DSL bank became shallower by about 10º, and the un-revetted

DSR slope became shallower by about 40º. There was a deep scour in the stream bed on the DSL side of the channel in 2016 which is no longer present in the 2017 cross-section. During field work it was noted that the scour had moved about 1 m downstream of the cross-section. This cross-section also had a shallow medial gravel bar in 2016, which was almost completely washed out in 2017 (Fig. 37).

Spatial Analysis of Stream Velocity

Viewing velocity measurements from each reach in map view reveals that velocities within the zone of roughness of cedar revetments decrease dramatically while velocities in non-revetted reaches decrease more slowly approaching the stream banks (Figures 38 through 45). In order to test the statistical significance of the impact of cedar revetments on near bank velocities, Getis Ord and Local Moran's I analysis were run on the velocity data. Getis Ord and Local Moran's I were run starting on the upstream end of Riceford Creek at reach 89 (see Figure 46). This reach does not have revetment along either bank and serves as a control reach as well as an analog to reach 88 and cross-section 6. The Getis Ord results from 2016 (Fig. 47) show that there is statistically significant clustering of high velocities along the DSL bank of the stream at reach 89. These have 90% to 99% confidence levels of being significantly higher velocities than would be expected if velocity were randomly distributed across the stream. We would expect to see similar distribution of high and low velocities in a similar reach that is revetted (a cut bank on an outside bend of a meander such as reach 88 and cross-section 6) if the revetment did not significantly impact stream velocity. There is also a cluster of significantly lower velocities on the DSR bank. The 2017 velocity measurements for this reach (Fig. 39) mirror the 2016 results.

Moran's I results for Reach 89 (Fig. 48) looks similar to the Getis Ord results, but it displays more low clusters of significant value. Local Moran's I from 2016 indicates that there are definite clusters of low velocity near, and north of, the island, with high velocity clusters along the south bank. There are only a couple outliers of low velocity surrounded by high velocity and they are in locations that make sense. As you get closer to the bank of the stream the friction on the water increases, which would lead to a decrease in velocity. This is demonstrated by the low-high outlier without revealing clusters of low velocities.

Cross-section 6 is along an outside meander and is comparable to control reach 88 with the difference of having cedar revetment on the DSL bank. There is only limited velocity data from 2017 (Fig. 40) and Getis Ord run with this limited data does not locate any significant clustering. Moran's I locates 2 outliers that happen to be next to each other. Because there are only 9 sample points in this reach, we cannot attach any statistical significance to these results. However, velocity data presents promising evidence that the cedar revetments greatly decrease near bank velocities as seen in reach 89.

An analysis of reach 8 reveals no significant clustering with Getis Ord in 2016 or 2017 (Fig. 49). Local Moran's I is also blank for the 2017 data, but reveals several clusters and outliers in the 2016 data (Fig. 50). This reach has revetment on the DSL bank and there are several low outliers behind and near the revetment line, with high clusters just outside of it. There is also clustering of low velocities along the DSR bank, with a couple high velocity outliers closer to mid-stream. These results further indicate that cedar revetments significantly decrease near bank velocities.

Reach 88 is another reach that has revetment along the DSL bank. Getis Ord (Fig. 51) from 2016 shows a very distinct difference in clustering in-front of and behind the cedars, as

well as significant clustering of hot spots on the DSR bank where there aren't any cedars. Local Moran's I (Fig. 52) echoes these results but includes a couple of low-high outliers along the DSR bank. The Sinclair reach (Fig. 45) had part of the revetment (on the DSR bank) ripped out during the September 2016 flood and there are not velocity measurements from 2016. There are not enough data points for a robust analysis of this reach.

Field Observations and Imagery Discussion

Most of the cedar revetments stayed intact during the 2016 flood and have varying degrees of embeddedness. Figure 53 shows a stream bank revetment that has been successfully stabilized. The toe of the stream bank has begun to embed sediment around the cedar tree and the upper part of the bank behind the revetment has stepped back to a lower slope angle, which has allowed vegetation to become established. This stream bank is in Revetment 4 (see Figure 28) which performed well during the September 2016 flood. Figure 33 is of a bank near cross-section 6 where the revetment has been almost entirely covered. There are just a few of the branches from the cedar sticking out of the soil and there is sediment in front of the revetments, such that the revetments are no longer along the edge of the stream. The bank behind the revetment is also shallow enough to walk up.

Figure 54 is a stream bank revetment that was damaged during the September 2016 flood. The photo is facing downstream and is from the south end of the Sinclair Reach, around the first bend from the bridge. The water coming from upstream travels along a long, straight reach of the channel headed straight for the area that failed along a > 90º bend (indicated by the red arrow in the inset photo). Figures 54 and 55 illustrate the model for revetment failure in these conditions. The arrow represents the flow of water focusing on a small part of the bank on the outer bend

during a flood. The blue polygon outlines where revetment was ripped out during the 2016 flood. Notice that downstream of the blue, the revetment is still in place. It is hypothesized that during high flow events a great deal of energy is focused on a small area of the bank (at the arrow tip). This energy washes out the shelf that forms at the toe of the bank in that spot (Fig. 55), undermining the revetment and cutting back into the bank. This compromises the strength of the anchor. The anchor eventually fails, and the revetment is ripped out exposing the bank to the direct erosive force of the water. A few meters downstream the flow is no longer aimed at the revetment, thus only a few meters are compromised. Figure 55 shows the models for both revetment success and failure.

The failure in revetment 9 is the only one that does not fit the model. Revetment 9 is on the outside of a curve that turns the river 180^{o}s and has a series of 3 small failures along it. It is also just downstream of a large failure in revetment 8. It is likely that debris from revetment 8 and other debris hit against this curve repeatedly during the flood. This combined with increased erosive force from the flood waters flowing directly toward the bank in these locations likely knocked out the revetments in Revetment 9.

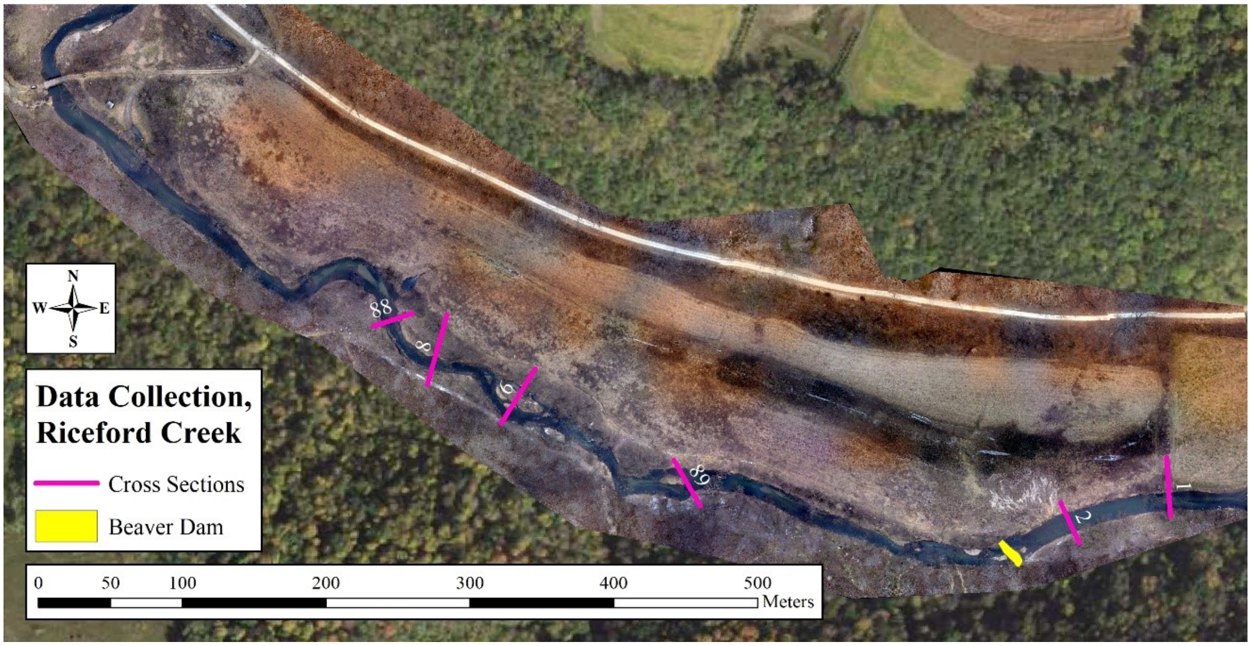


Figure 28. Locations of Cross-Sections in Lea and Sinclair reaches. A beaver Dam was downstream of cross-section 2 in 2016. It had been washed out by the 2017 field season.

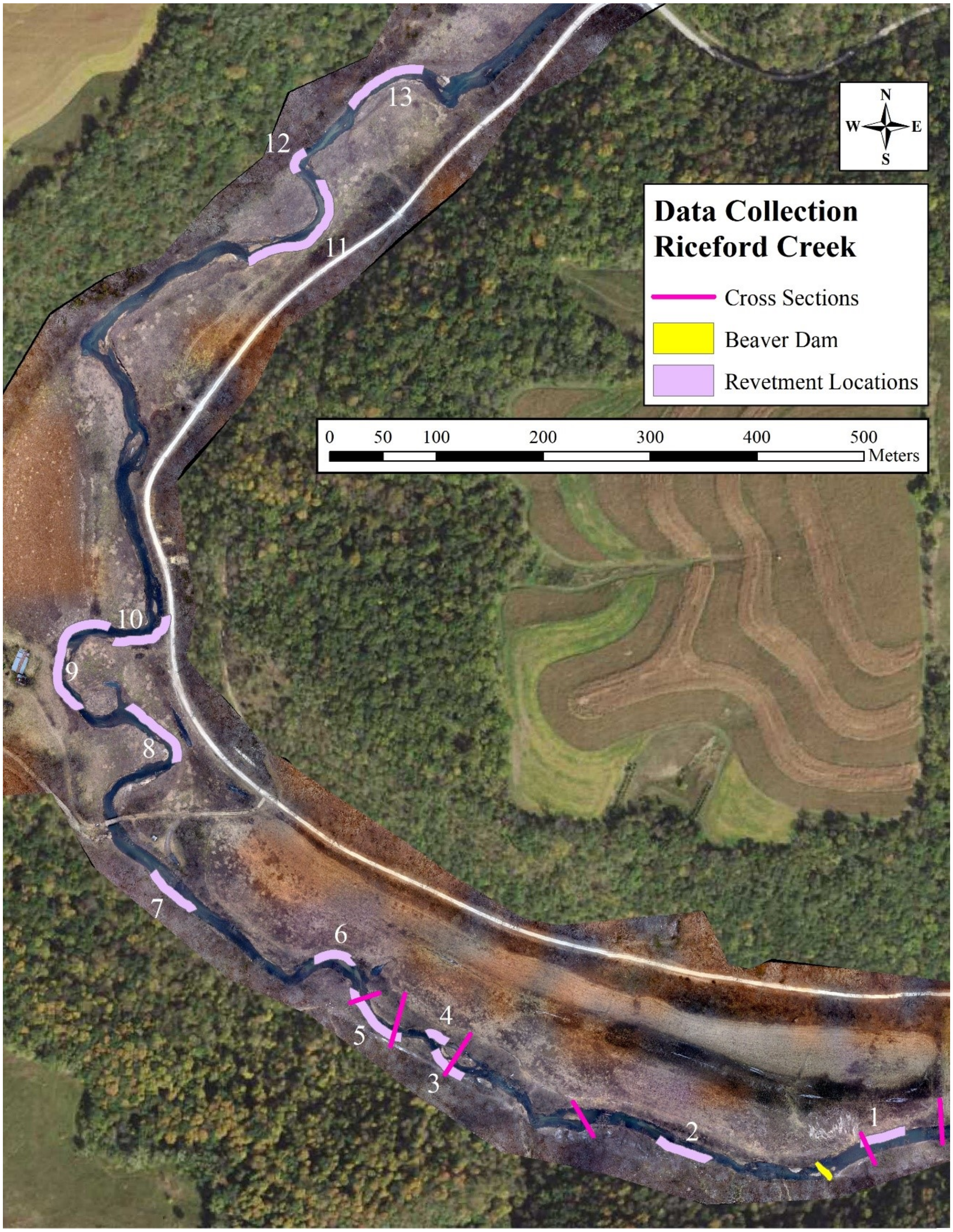


Figure 29. Locations where cedar revetments were placed along the Lea and Sinclair reaches.

Table 1. Net erosion in Lea and Sinclair reaches. Erosion is divided into revetted areas and non-revetted areas. Accuracy for erosion measurements is ± 0.1 m.

Revetment Installed	Average Erosion (m)	Length of Stream Bank (m)
Yes	-0.25	771
No	-0.31	3420
All Points	-0.30	4191

Table 2. Stream bank change during the September 2016 flood in the Lea and Sinclair Reaches. Positive values are accretion (i.e. deposition) and negative values are erosion. The locations of the revetments are shown in Figure 29. The 'Average Erosion' represents the net change for the full length of revetted streambank, including erosion that occurred to damaged portions of the revetment. For revetments where a portion of the revetment was damaged or removed by the flood, the net erosion for the intact and damaged portions of the revetment are also provided. This demonstrates that even when a portion of the revetment is damaged, the remaining intact sections still reduce bank erosion rates. Accuracy for erosion measurements is ± 0.1 m.

	Erosion (m) in each Revetment			
Revetment ID	Average Erosion	Average Erosion Intact Portion	Average Erosion Damaged Portion	Status
5	0.22			Intact
12	0.13			Intact
7	-0.01			Intact
2	-0.02			Intact
4	-0.04			Intact
10	-0.16			Intact
8	-0.22	0.09	-1.38	Damaged
9	-0.31	-0.26	-0.97	Damaged
3	-0.36			Intact
13	-0.42	-0.29	-1.12	Damaged
6	-0.53	-0.42	-0.62	Damaged
11	-0.58			Intact

Table 3. Net erosion in revetted areas in the Lea and Sinclair Reaches, showing the difference between revetments that worked and those that failed. The 61 meters that failed heavily skew the results in Table 1 for average erosion for revetted reaches. Note: The status of 9 m (1.2%) of the 710 m of streambank that were revetted was unable to be determined and are included as "Intact" in the calculations. Accuracy for erosion measurements is ± 0.1 m.

Revetment Status	Average Erosion (m)	Length of Stream Bank (m)
Intact	-0.19	710
Damaged	-0.98	61

Table 4. Net erosion in comparison to the BEHI adjective rating along the Lea and Sinclair reaches. No reaches with Extreme or Very Low BEHI ratings were revetted. Accuracy for erosion measurements is ± 0.1 m.

	Stream Length (m)					Erosion (m)				
BEHI Adjective Rating	Un-Revetted Stream bank	Revetted Stream bank	Stream bank with Intact Revetment	Stream bank with Damaged Revetment	Total Stream length	Average Erosion Un-Revetted	Average Erosion Revetted	Average Erosion Intact Portion	Average Erosion Damaged Portion	Total Average Erosion
Extreme	101	-	-	-	101	-0.86	-	-	-	-0.86
Very High	11	17	17	-	28	-0.18	0.19	0.19	-	0.04
High	622	517	456	61	1139	-0.24	-0.32	-0.24	-0.98	-0.28
Moderate	1606	223	223	-	1829	-0.30	-0.09	-0.09	-	-0.28
Low	747	14	14	-	761	-0.44	-0.47	-0.47	-	-0.44
Very Low	47	-	-	-	47	-0.27	-	-	-	-0.27

Table 5. Net erosion in BEHI adjective groups. Accuracy for erosion measurements is ± 0.1 m.

	Stream Length (m)					Erosion (m)				
BEHI Adjective Rating	Un-Revetted Stream bank	Revetted Stream bank	Stream bank with Intact Revetment	Stream bank with Damaged Revetment	Total Stream length	Average Erosion Un-Revetted	Average Erosion Revetted	Average Erosion Intact Portion	Average Erosion Damaged Portion	Total Average Erosion
Extreme to High	734	534	473	61	1268	-0.31	-0.31	-0.23	-0.98	-0.31
Moderate to Very Low	2400	237	237	-	2637	-0.35	-0.11	-0.11	-	-0.33
None Determined	287	-	-	-	287	-0.12	-	-	-	-0.12
All	3420	771	710	61	4191	-0.31	-0.25	-0.19	-0.98	-0.30

Table 5a. Net erosion in BEHI adjective groups combining “Damaged” and “Unrevetted” streambank measurements. Accuracy for erosion measurements is ± 0.1 m.

Stream Length (m)				Erosion (m)		
BEHI Adjective Rating	Un-revetted bank + Damaged bank	Streambank with Intact Revetment	Total Stream length	Average Erosion Un-Revetted + Damaged	Average Erosion Intact	Total average Erosion
Extreme to High	795	473	1268	-0.36	-0.23 (36%)	-0.31
Moderate to Very Low	2400	237	2637	-0.35	-0.11 (69%)	-0.33

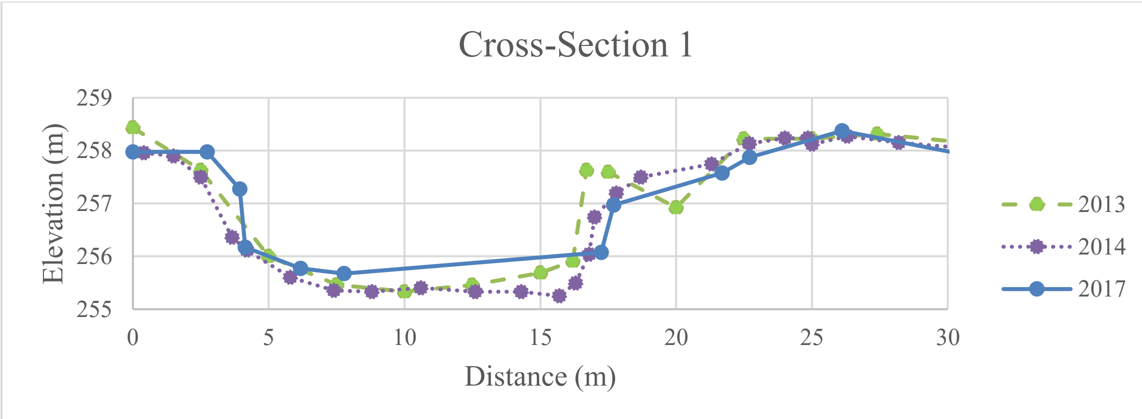


Figure 30. Cross-Section 1 did not receive any revetment treatment. This is located upstream of the beaver dam noted in 2016. The 2017 line is shallower than the previous years, likely partially due to increased sedimentation upstream of the dam.

Table 6. Cross-Section 1 channel measurements.

Cross-Section 1			
Year	2013	2014	2017
Channel Width (m)	11.2	12.6	13.1
DSL Bank Height (m)	1.6	1.8	1.67
DSL Bank Slope	33º	34º	50º
DSR Bank Height (m)	1.7	1.9	0.87
DSR Bank Slope	74º	42º	60º

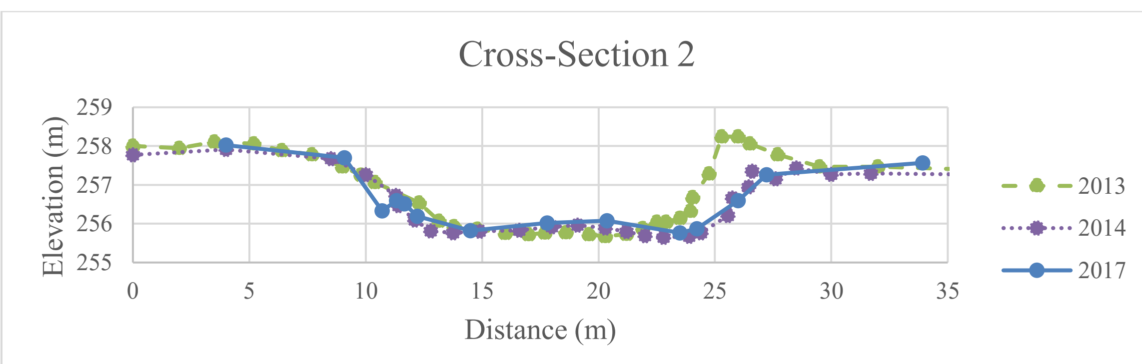


Figure 31. Cross-Section 2 was revetted on the DSR bank. This is located upstream of the beaver dam noted in 2016. The 2017 line is shallower than the previous years, likely partially due to increased sedimentation upstream of the dam.

Table 7. Cross-Section 2 channel measurements.

Cross-Section 2			
Year	2013	2014	2017
Channel Width (m)	12.75	14.95	15.29
DSL Bank Height (m)	1.4	1.9	1.5
DSL Bank Slope	19º	24º	26º
DSR Bank Height (m)	2.1	1.15	1.3
DSR Bank Slope	49º	48º	23º

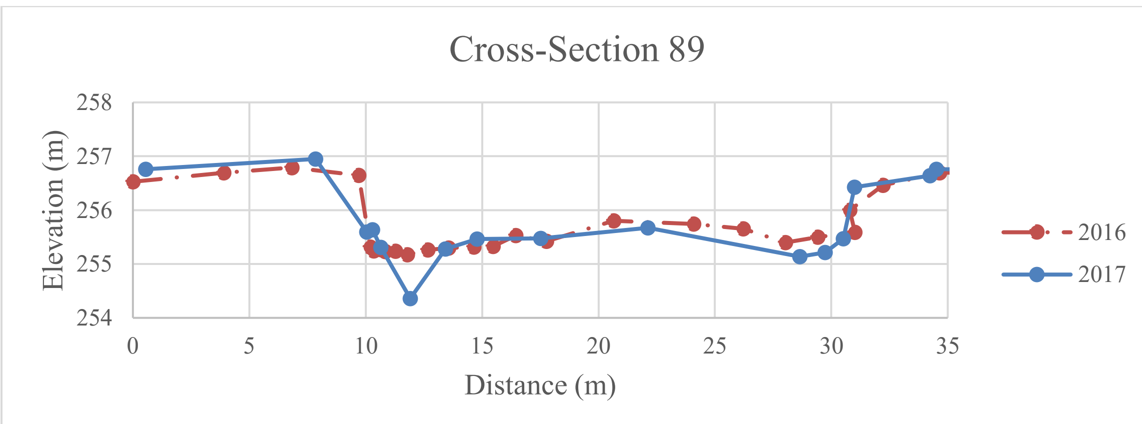


Figure 32. Cross-Section 89 did not get revetted. It was determined to be an analog to Cross-Section 88

Table 8. Cross-Section 89 channel measurements.

Cross-Section 89		
Year	2016	2017
Channel DSL to Island (m)	10.31	11.73
Channel Width (m)	20.12	20.12
DSL Bank Height (m)	1.33	1.64
DSL Bank Slope	64º	33º
DSR Bank Height (m)	0.84	0.96
DSR Bank Slope	35º	63º

Figure 33. Revetment 3, just upstream of cross-section 6. The picture is taken looking downstream on the DSL bank. The revetment is being incorporated into the stream bank.

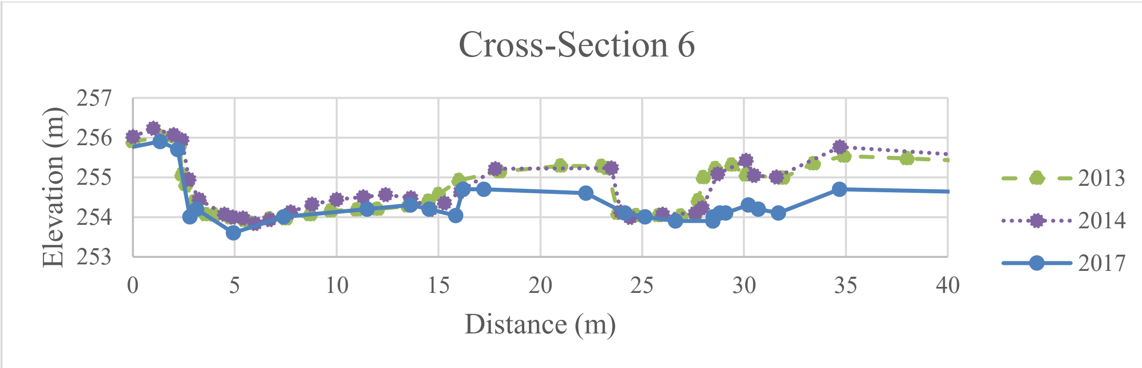


Figure 34. Cross-Section 6 was revetted on the DSL bank.

Table 9. Cross-Section 6 channel measurements.

Cross-Section 6			
Year	2013	2014	2017
Channel Width (m)	24.6	23.45	25.68
Channel DSL to Small Island (m)	-	6.8	8.69
Channel DSL to Main Island (m)	10.5	10.8	13.04
DSL Bank Height (m)	1.44	1.5	1.32
DSL Bank Slope	60º	60º	55º
DSR Bank Height (m)	1.15	1.0	0.4
DSR Bank Slope	49º	42º	13º
Small Island Width (m)	-	3.3	3
Main Island Width (m)	9.3	8.7	7.17
Main Island Height (m)	0.85	0.93	0.37
DSR Channel (m)	3.8	4	4.34

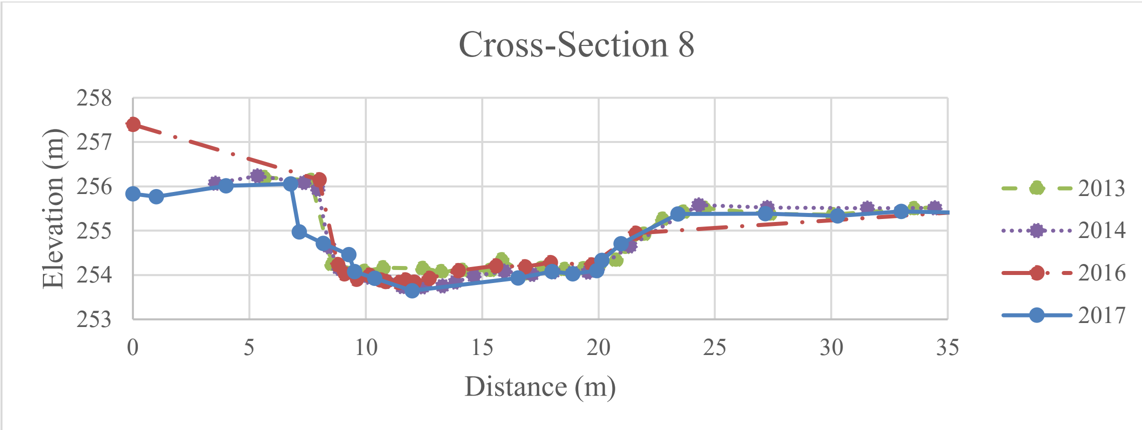


Figure 35. Cross-Section 8 was revetted on the DSL bank. The 2013 data appears much shallower in the channel than all other years. We believe the elevations in the channel are inaccurate, since this is where the 2013 water elevations graph. The data was likely recorded wrong during collection. Even though elevations are off, the channel width and shape are still reasonably accurate.

Table 10. Cross-Section 8 channel measurements.

Cross-Section 8				
Year	2013	2014	2016	2017
Channel Width (m)	11.5	11.1	10.9	10.4
DSL Bank Height (m)	1.9	1.94	2.07	1.98
DSL Bank Slope	65º	52º	69º	36º
DSR Bank Height (m)	1.24	1.44	0.72	1.28
DSR Bank Slope	15º	18º	21º	20º
DSL Upper Bank Height (m)	-	-	-	1.08
DSL Upper Bank Slope	-	-	-	71º
DSL Lower Bank Height (m)	-	-	-	1.06
DSL Lower Bank Slope	-	-	-	18º

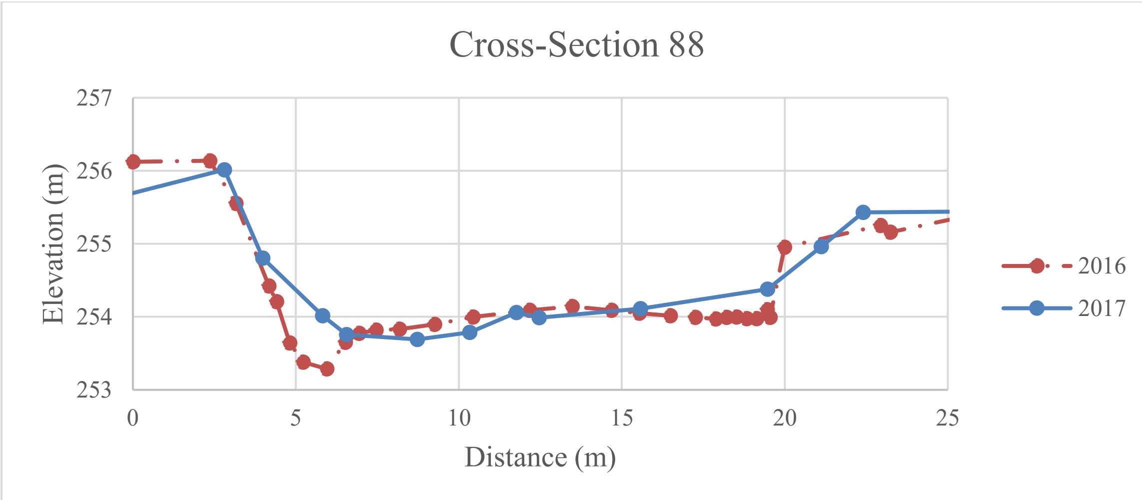


Figure 36. Cross-Section 88 was revetted on the DSL bank. Analog to Cross-Section 89.

Table 11. Cross-Section 88 channel measurements.

Cross-Section 88		
Year	2016	2017
Channel Width (m)	15.38	12.91
DSL Bank Height (m)	1.93	1.94
DSL Bank Slope	43º	37º
DSR Bank Height (m)	0.88	0.85
DSR Bank Slope	63º	16º

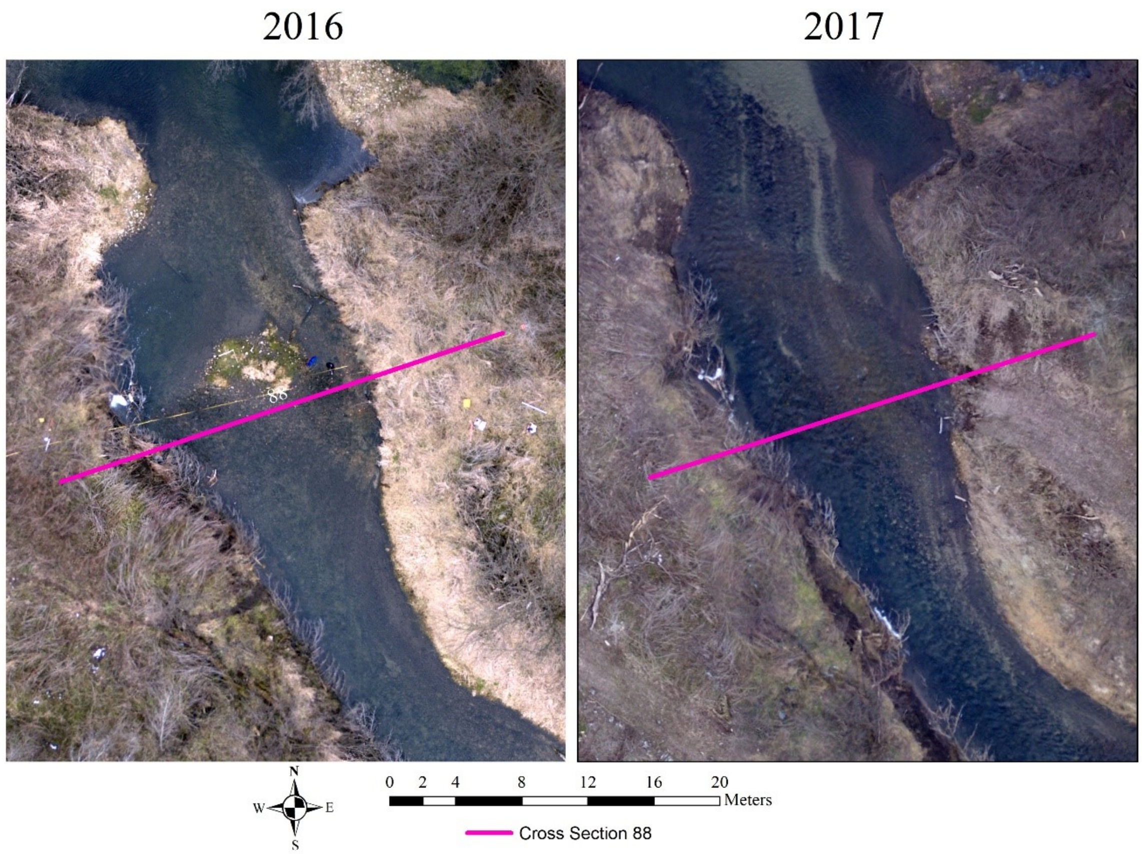


Figure 37. Drone imagery of cross-section 88, showing the presence of a medial gravel bar in 2016. In 2017 the gravel bar was washed out.

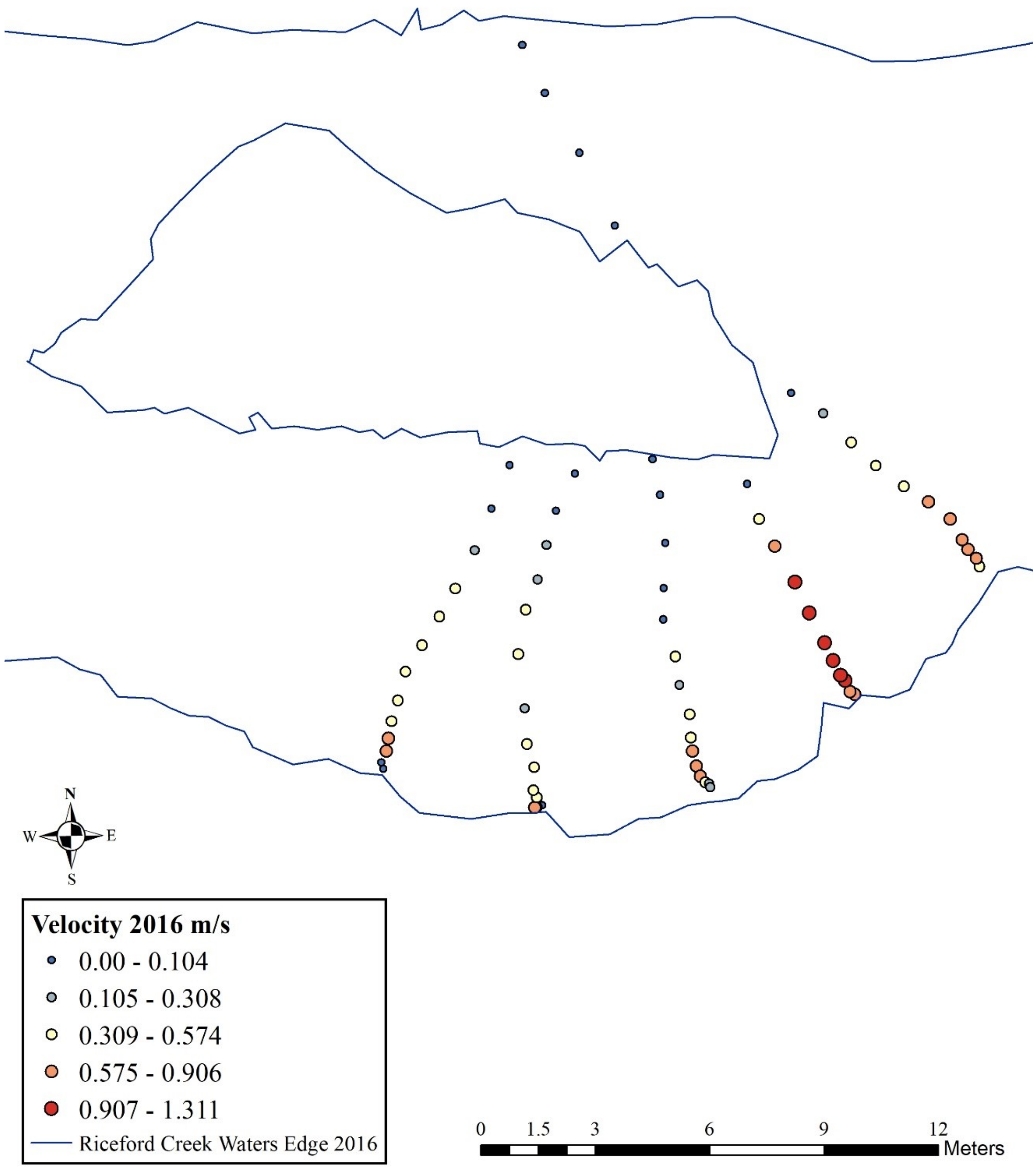


Figure 38. Velocity data from 2016 in Reach 89.

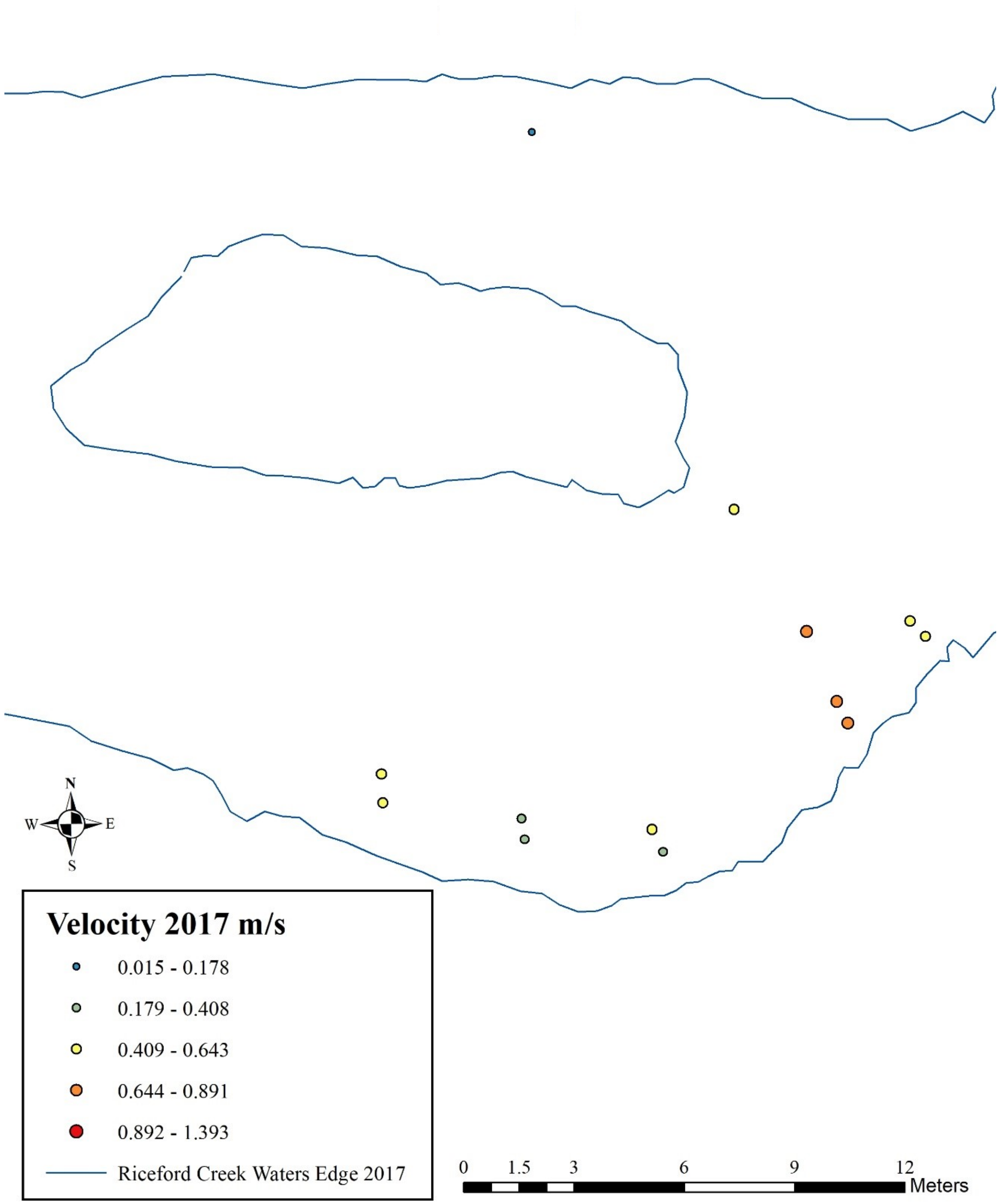


Figure 39. Velocity along Reach 89 in 2017.

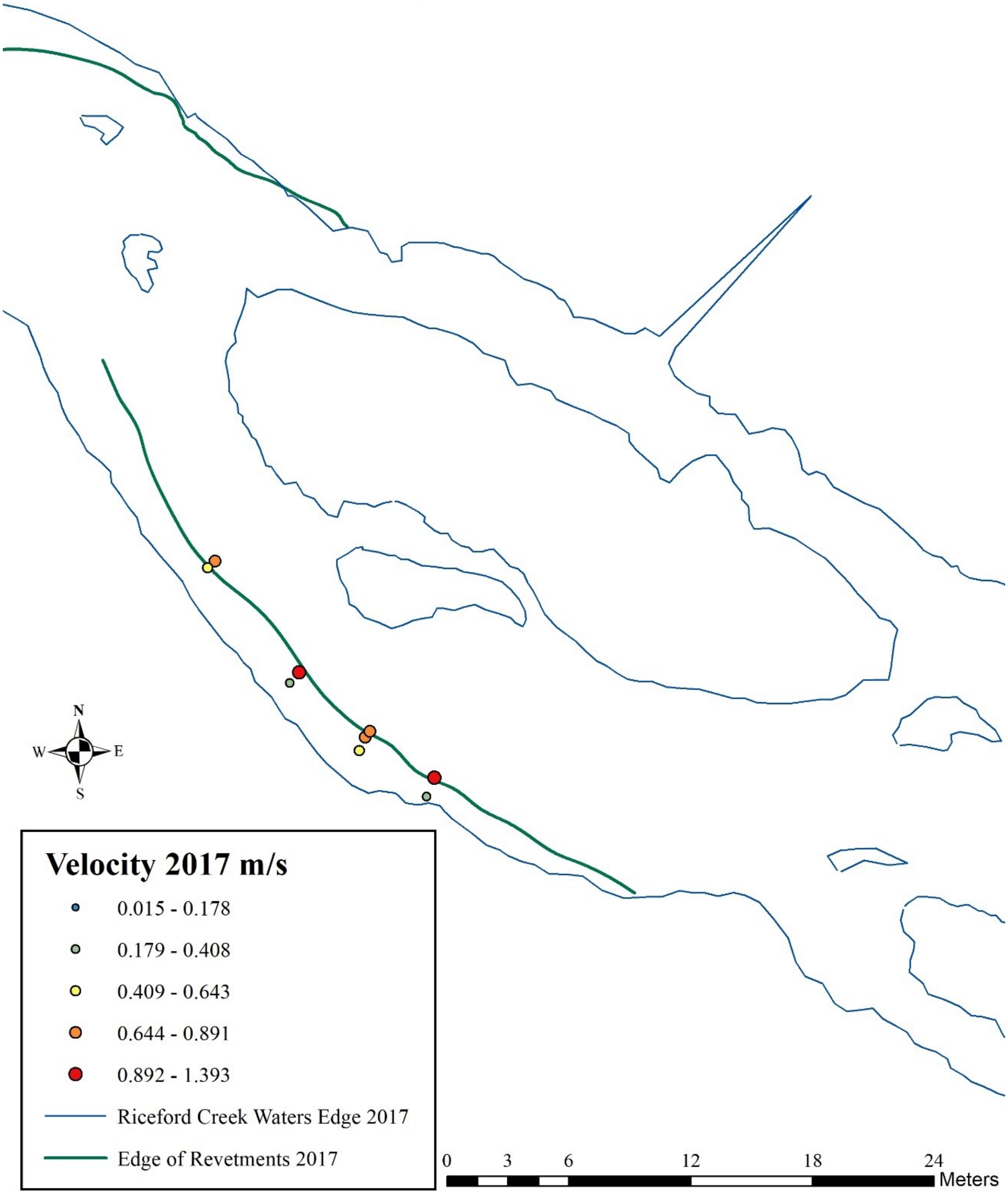


Figure 40. Velocity near Cross-section 6. Velocities are very high near and outside of the cedar revetment line but drop when measured inside the influence of the revetments. Only 2017 data are available.

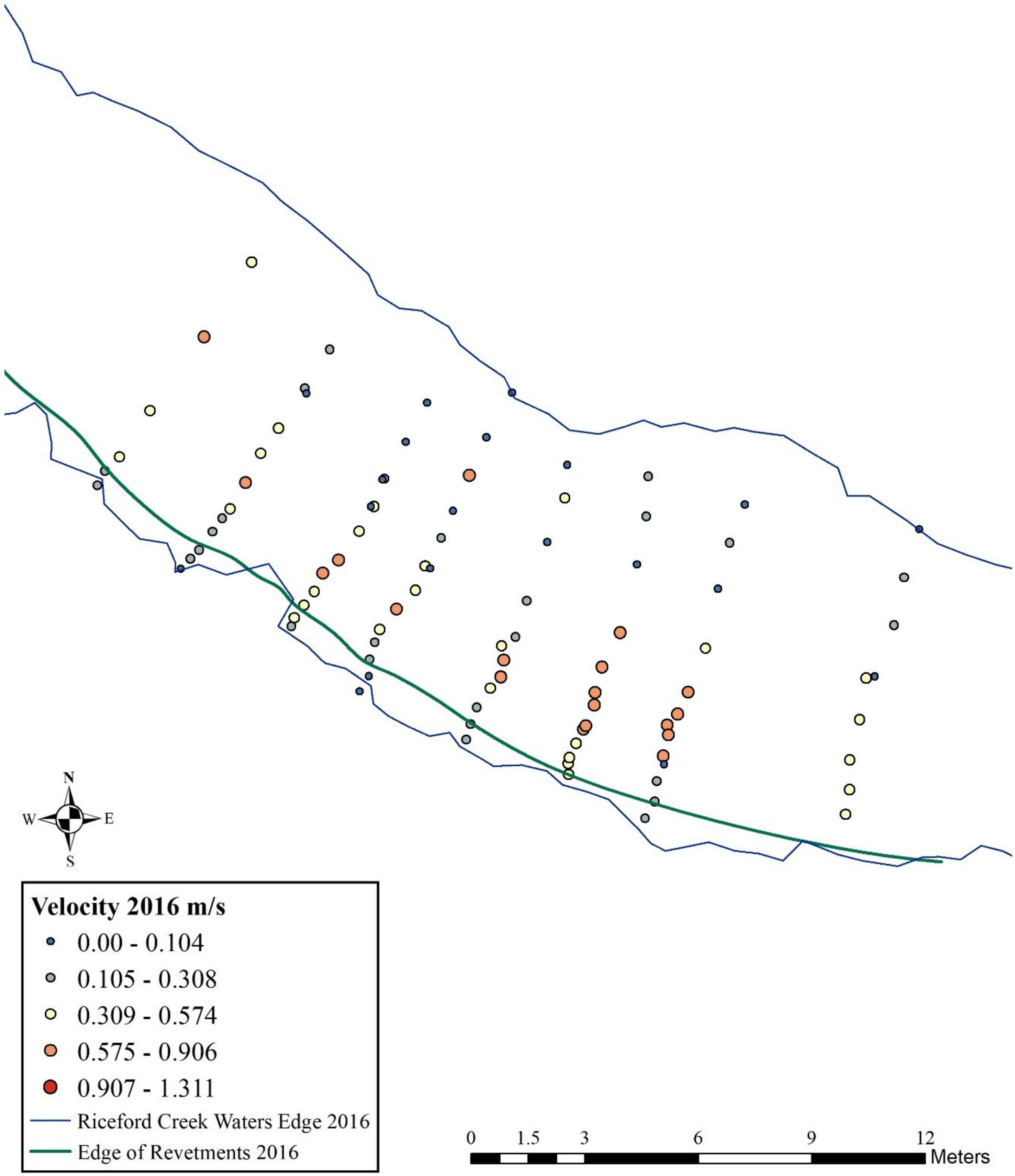


Figure 41. Velocity data from 2016 in Reach 8.

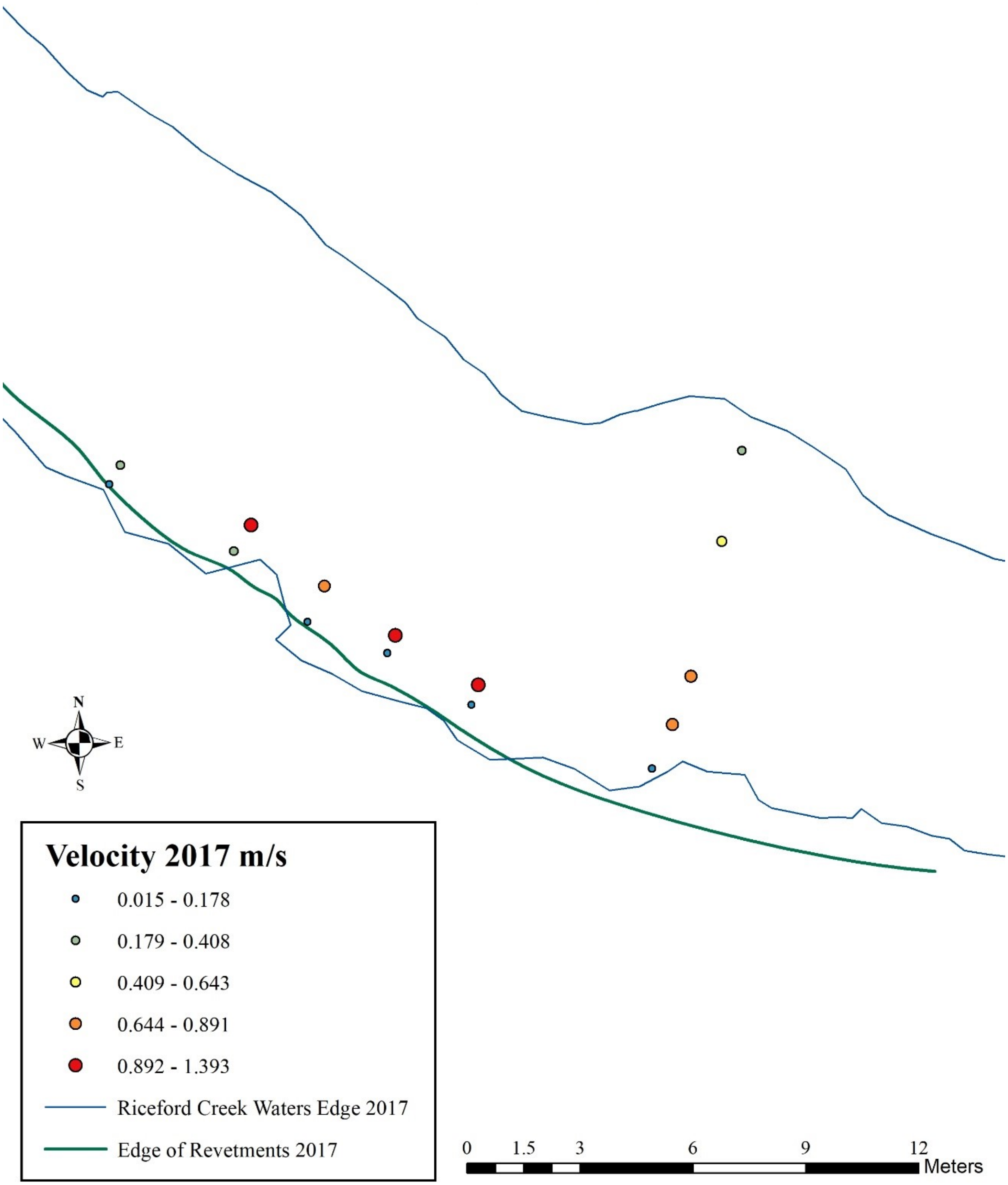


Figure 42. Velocities along Reach 8 in 2017.

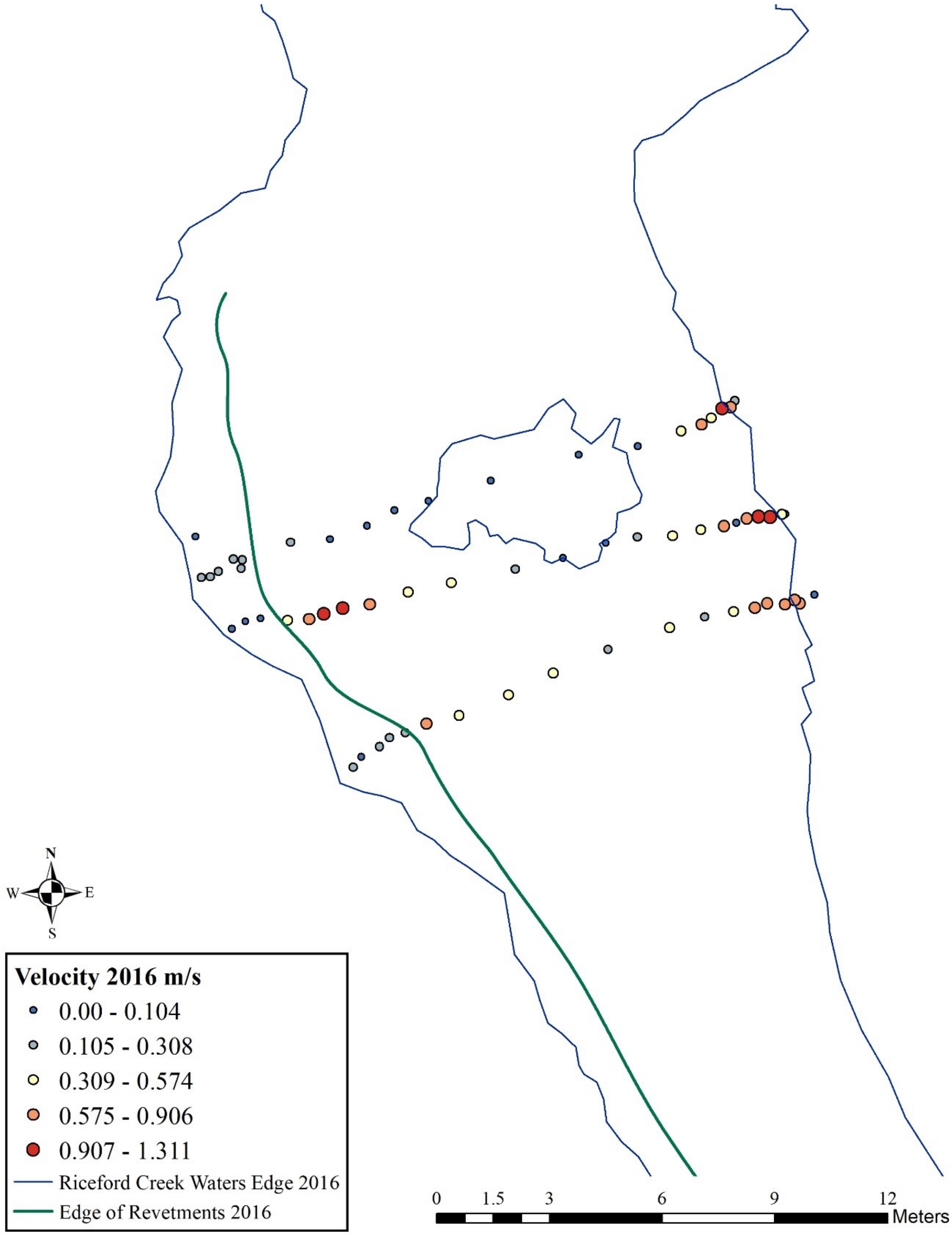


Figure 43. Velocity data from 2016 in Reach 88.

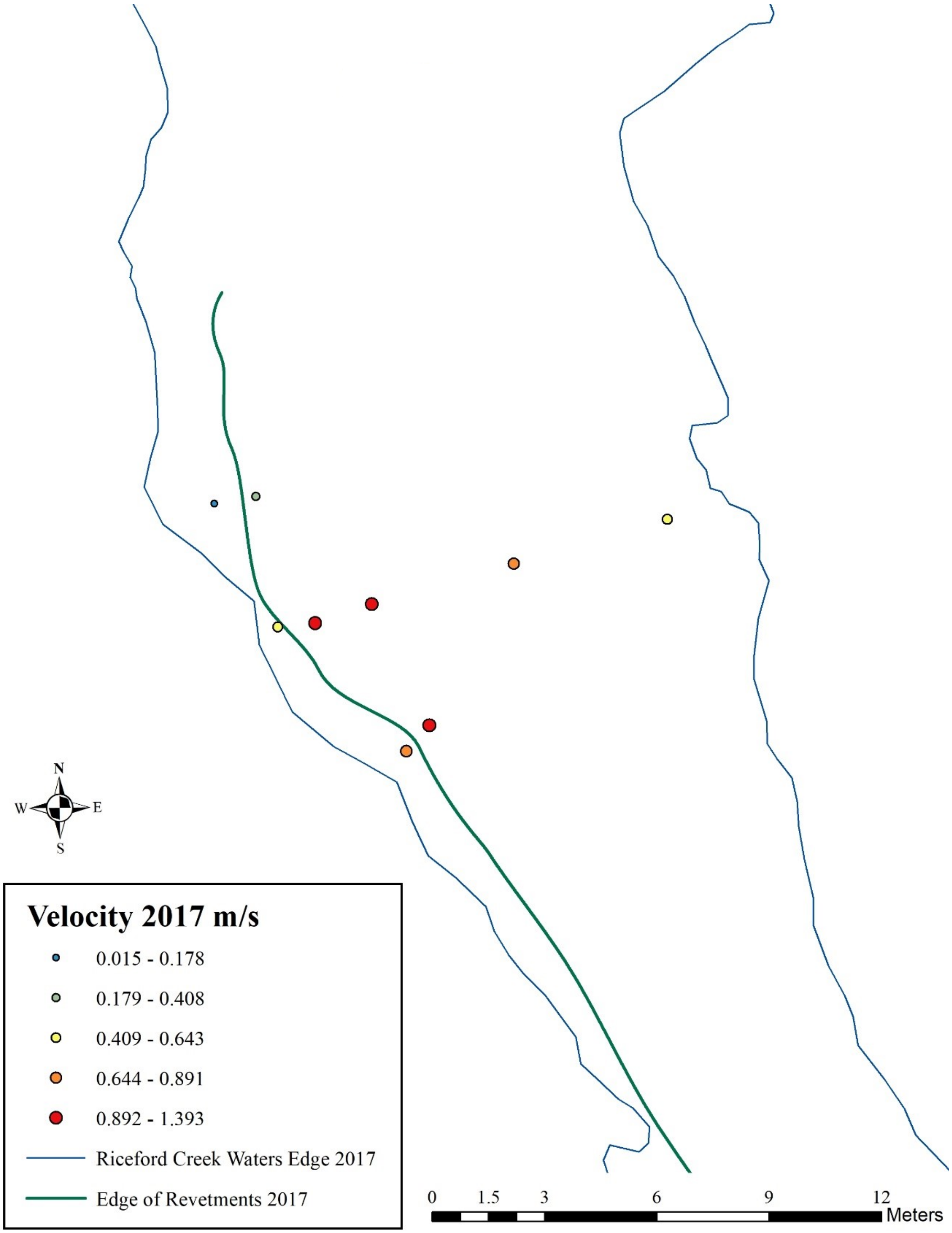


Figure 44. Velocities along Reach 88 in 2017.

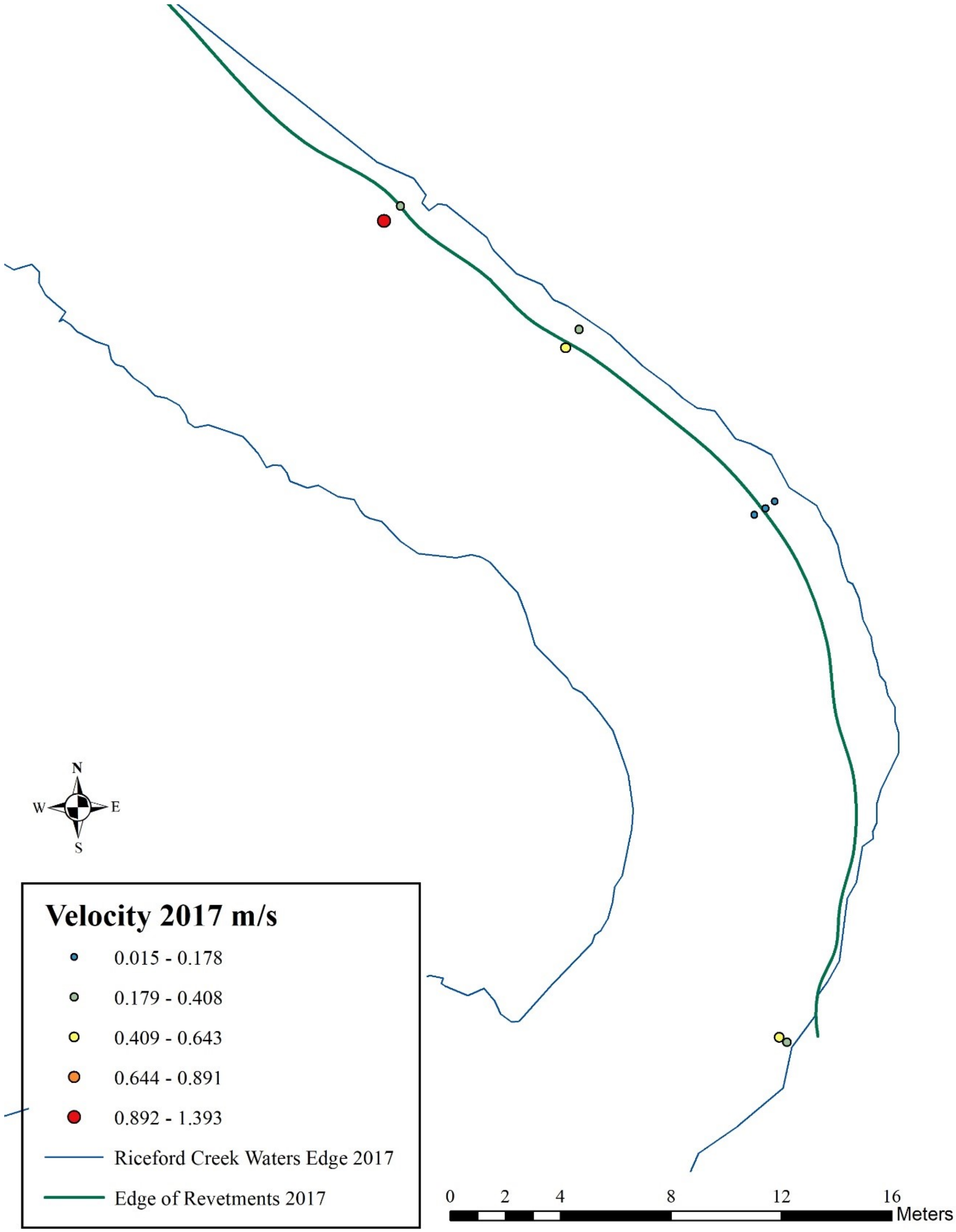


Figure 45. Results from Velocity collection for Sinclair 1. Only 2017 data were available.

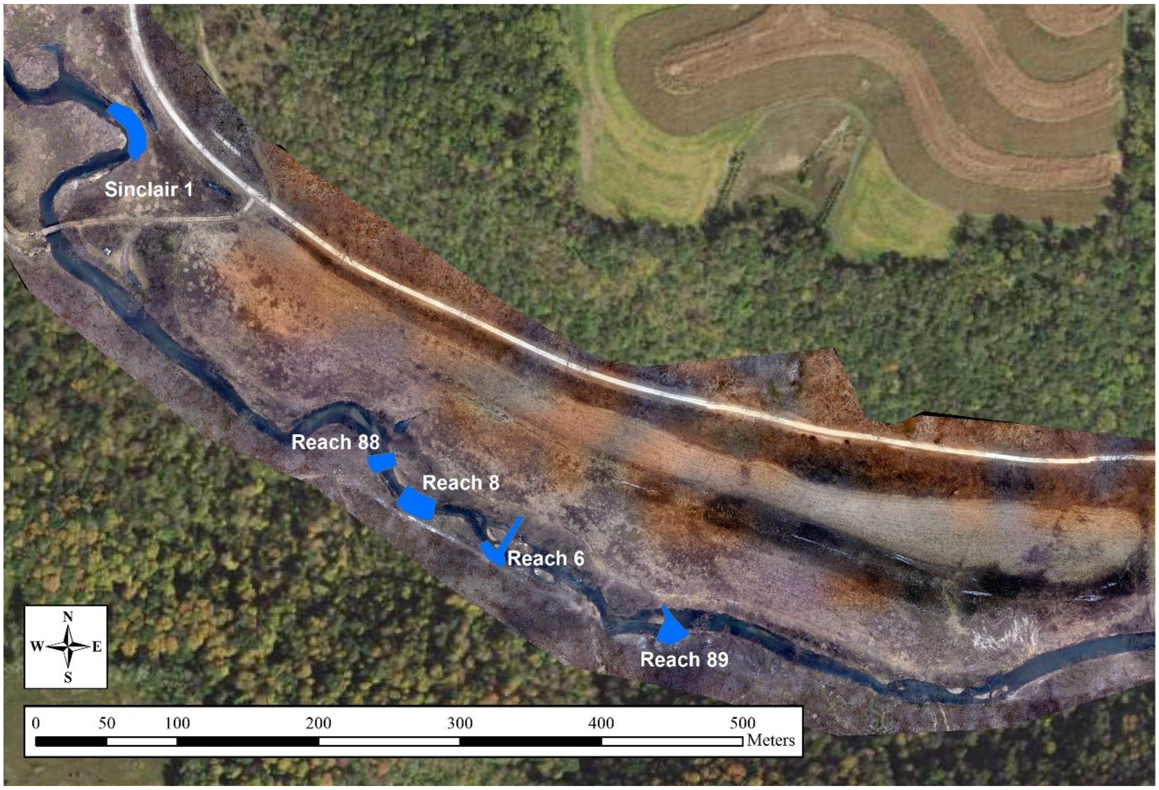


Figure 46. Reaches where velocity was collected. Getis Ord and Morans I were run on the 2016 data from Reaches 89, 8, and 88.

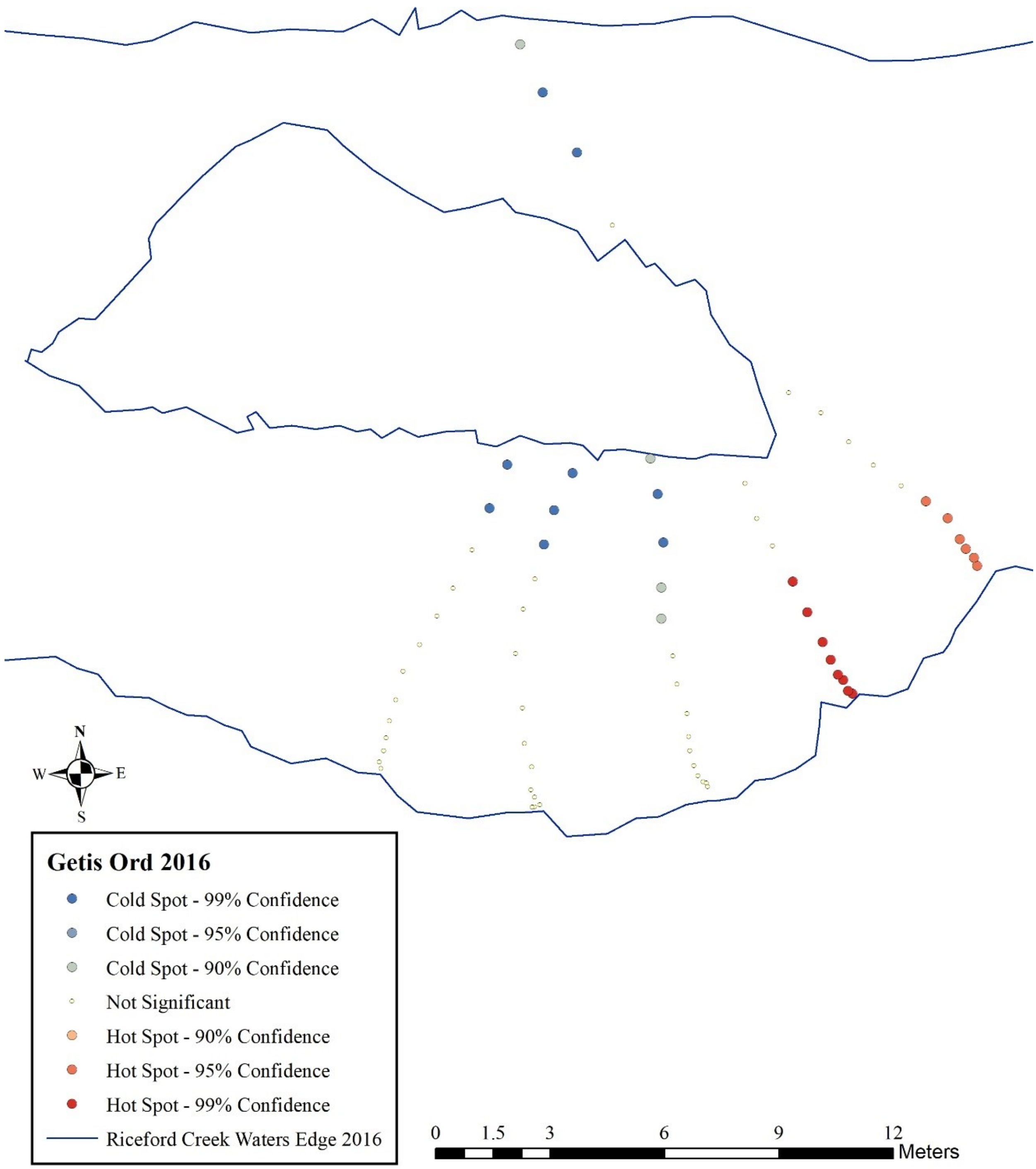


Figure 47. Results from Getis Ord for Reach 89, run with 2016 velocity data. This analysis shows where high and low velocities are statistically significant.

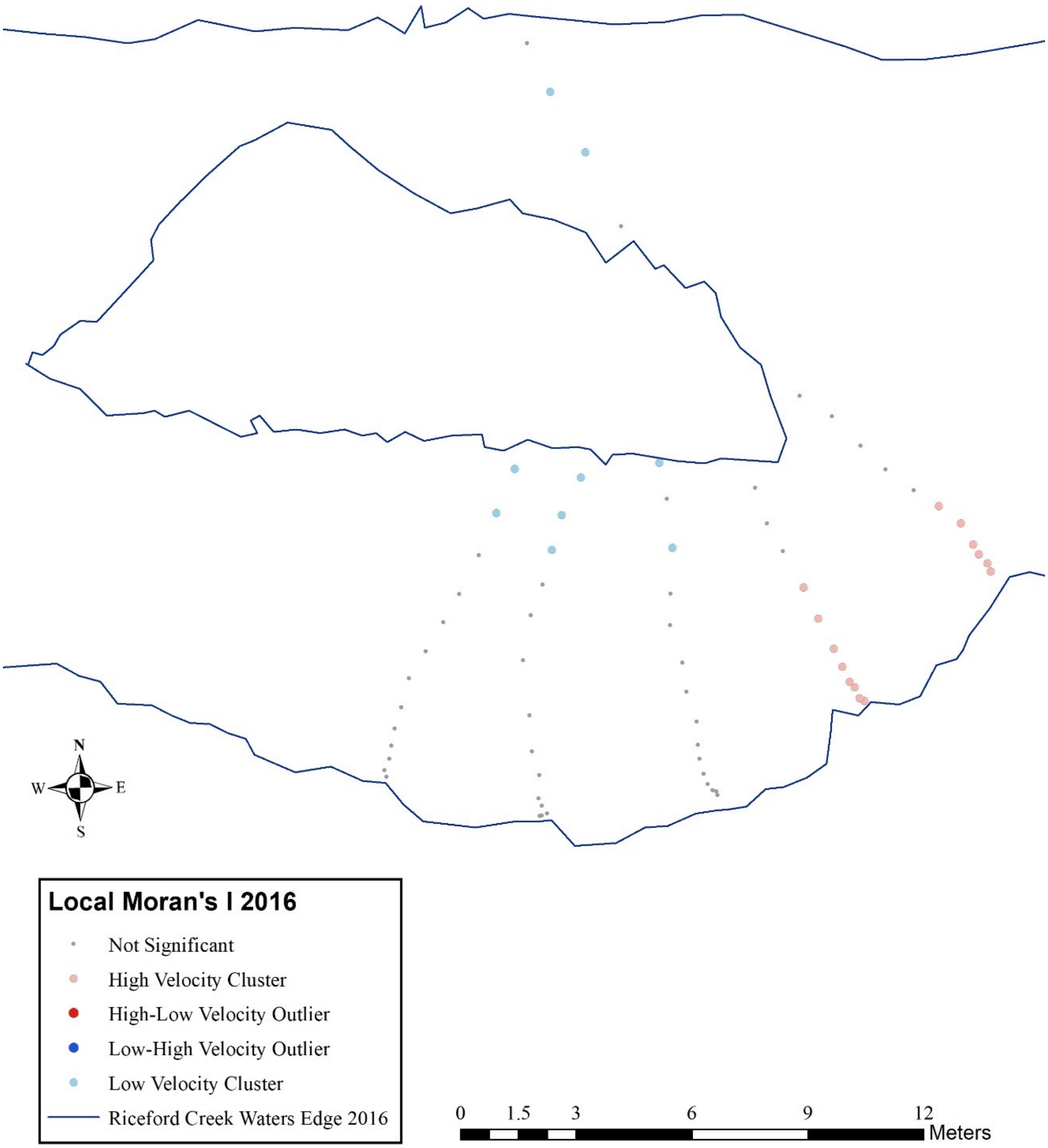


Figure 48. Results from Local Morans I for Reach 89, run with 2016 data, showing where high and low velocities are statistically significant.

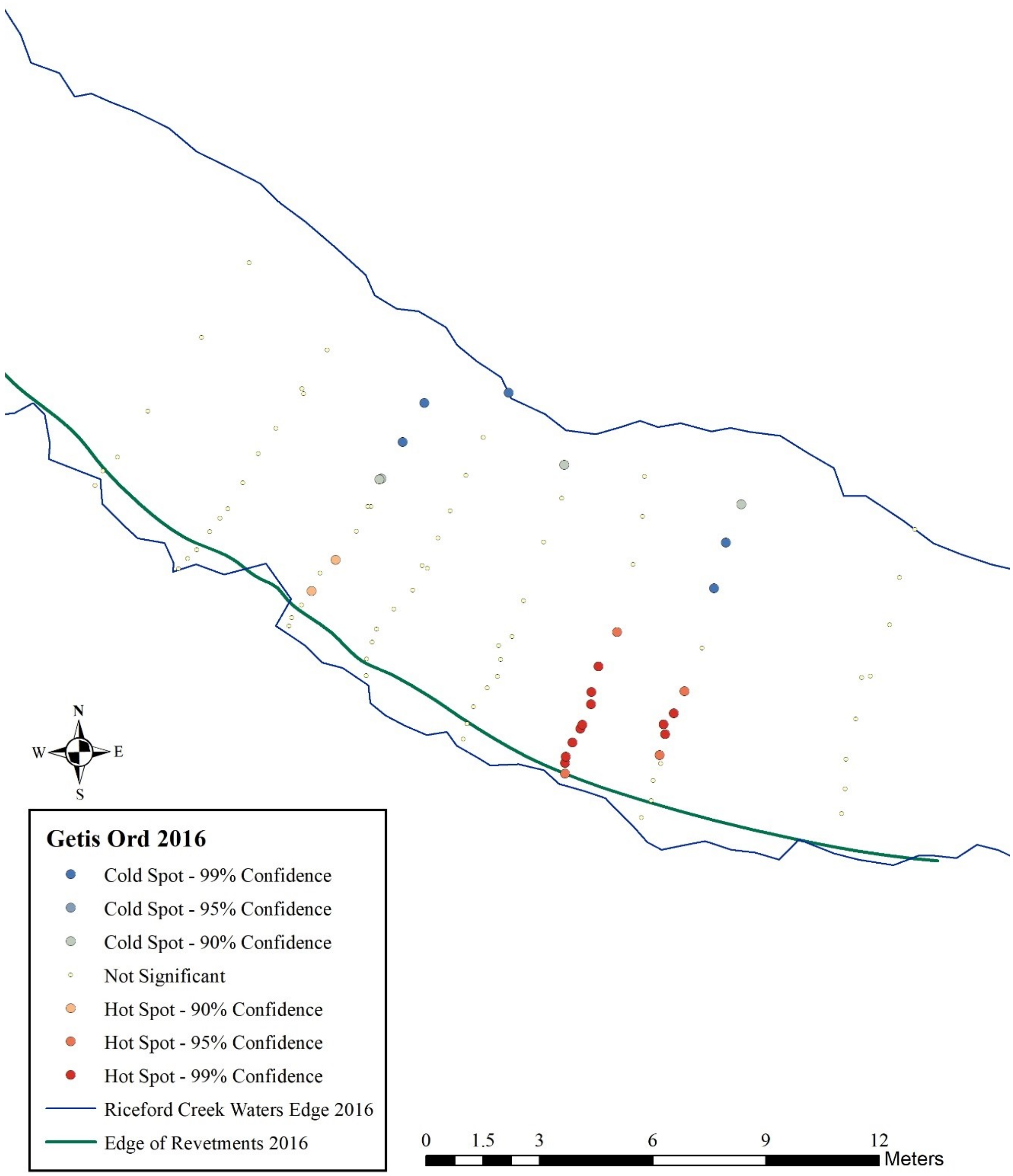


Figure 49. Results from Getis Ord in Reach 8 run with 2016 velocity data.

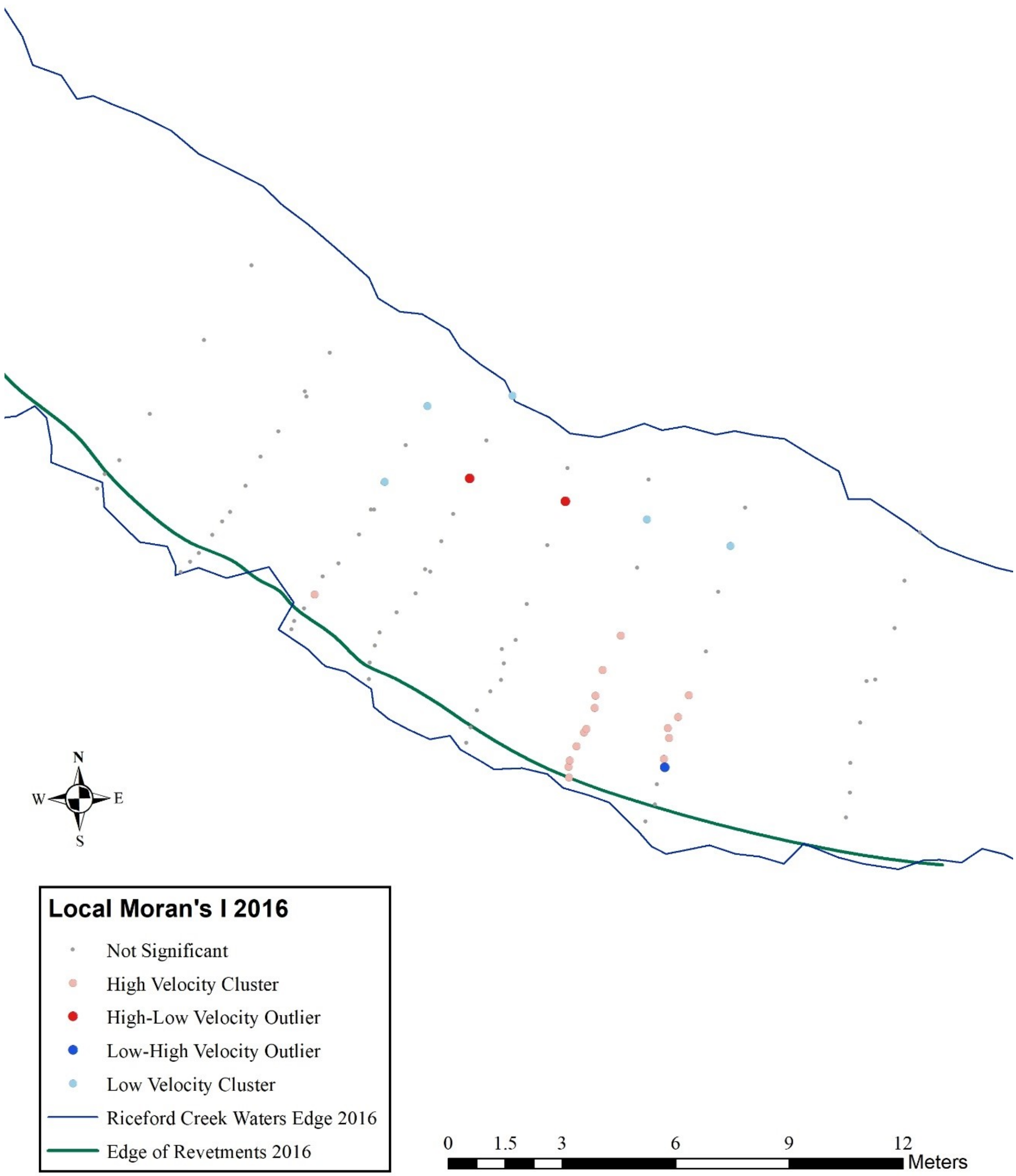


Figure 50. Results from Local Morans I in Reach 8, run with 2016 velocity data.

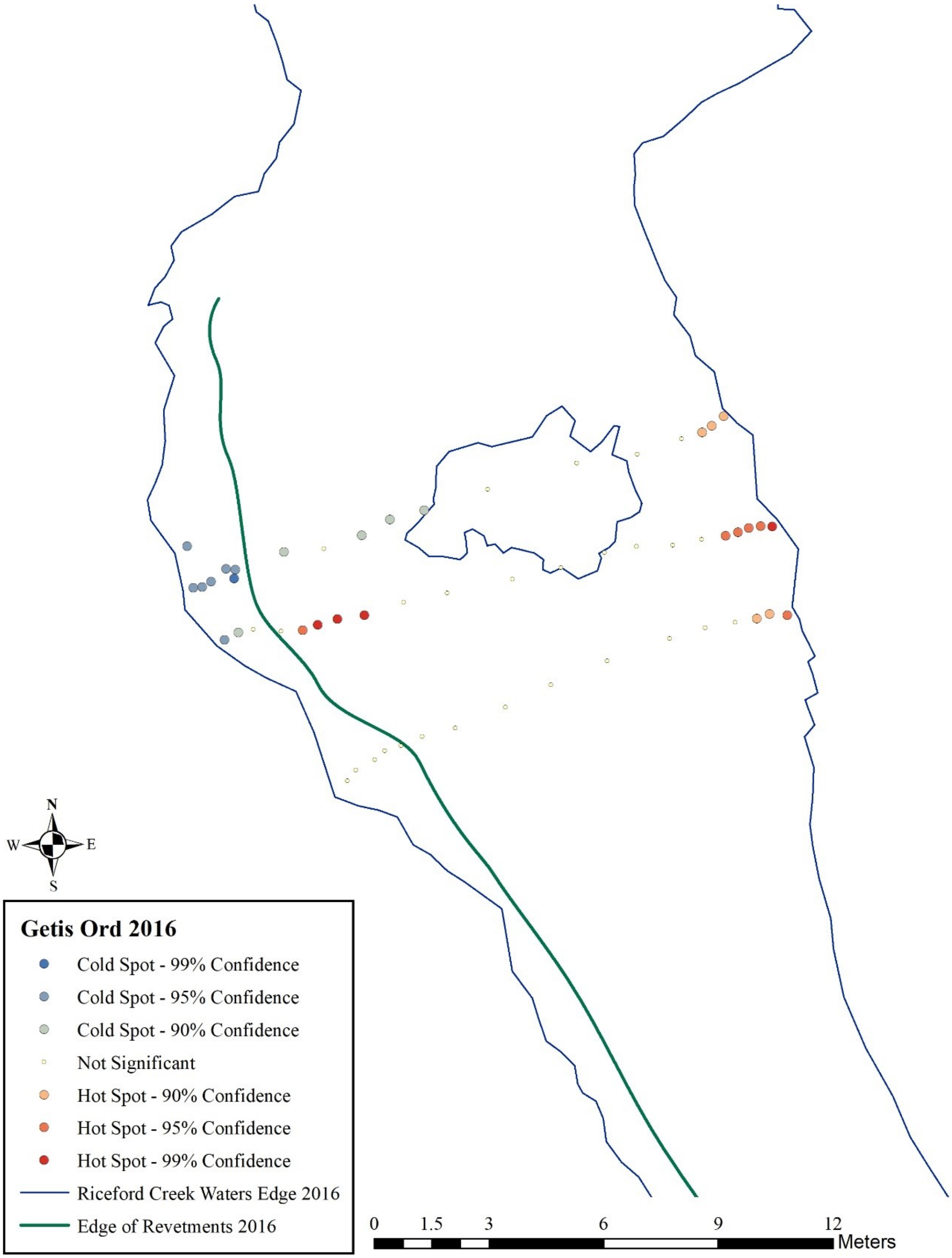


Figure 51. Results from Getis Ord in reach 88, run with 2016 velocity data.

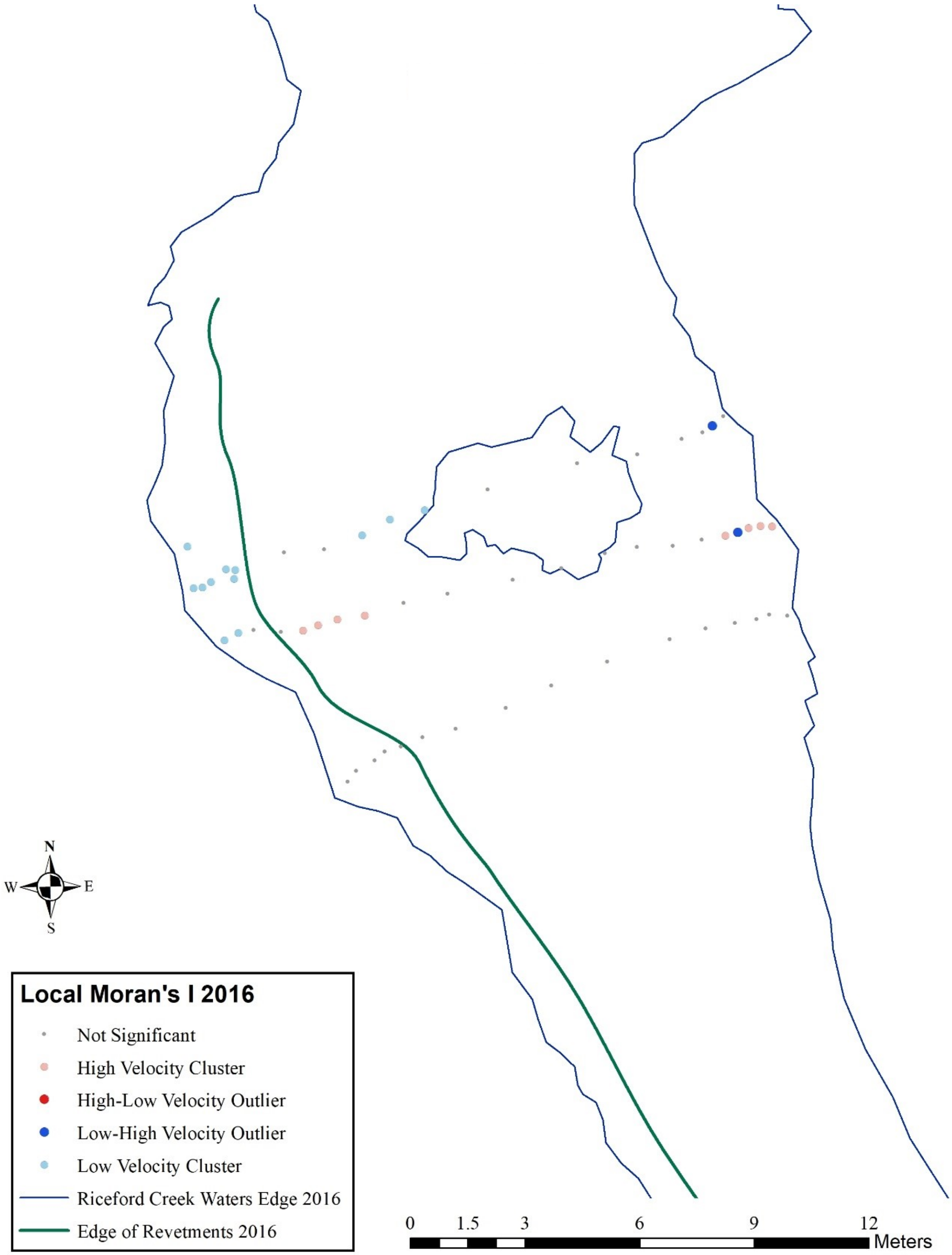


Figure 52. Results from Local Morans I for Reach 88, run with 2016 velocity data.

Figure 53. Working Revetment with embedded tree branches, low angle bank slope, and grasses/vegetation growing. This is in Revetment 4.

Figure 54. A stream bank revetment at Sinclair 1 that partially failed during the September 2016 flood. The photo is facing downstream and is from the south end of the Sinclair Reach, around the first bend from the bridge. The water coming from upstream travels along a long straight portion of the channel headed straight for the upstream portion of the revetment that failed (as indicated by the red arrow in the inset photo).

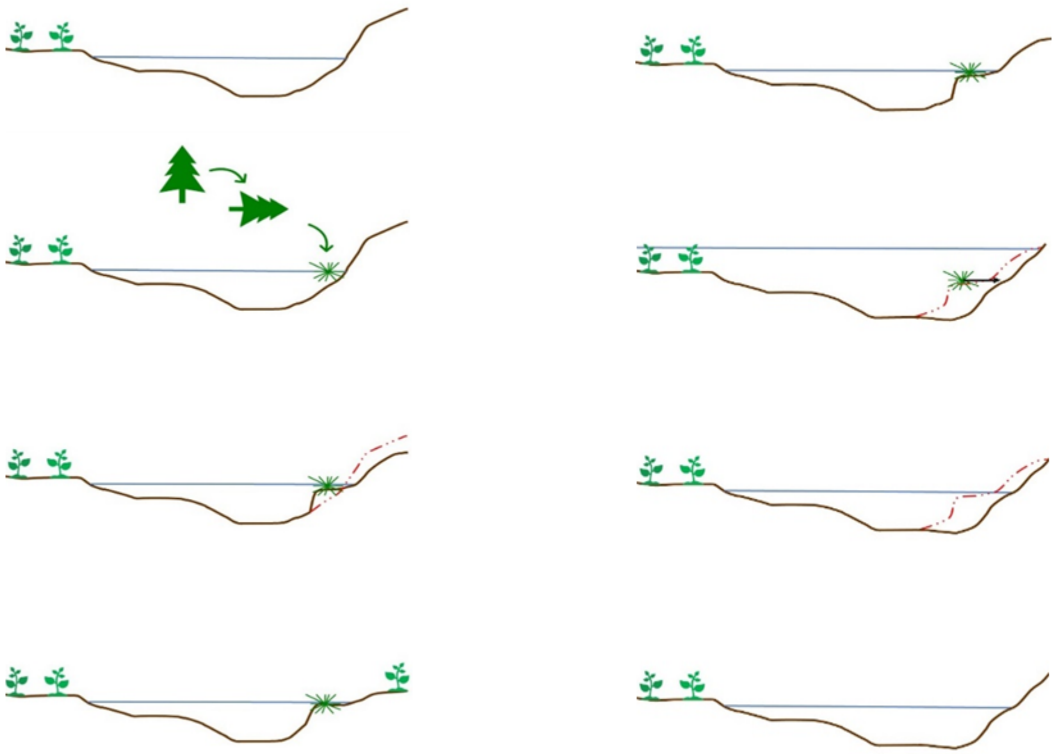


Figure 55. Diagram for Revetment Success (left) and Failure (right) based on observations made after an approximately 50-year flood event. Ceders are anchored to the bank (see Figure 9) stabilizing the toe and allowing material to collapse from the bank without bank retreat. The material forms a shelf of sediment under and around the cedar and once the bank is shallow enough, grasses and other small vegetation grow on the bank and provide protection during subsequent floods. The right image shows that the shelf is washed out during a high flow. When this loosens the anchor, it can wash out the cedar as well. Then the bank starts to step back again instead of becoming shallower and stabilizing.

CONCLUSION

Cedar Revetments installed in Riceford Creek mitigate streambank erosion. They significantly reduce the amount of sediment lost from stream banks when compared to non-revetted reaches. Cedar revetments create roughness along the stream banks that reduce flow velocity and mitigate stream power. This allows bank stabilization, and in some cases, sediment accretion to occur. Further, the stabilization and accretion provide accommodation space to capture and store slumped material which allows the bank slope to decrease and support the growth of vegetation that in turn further stabilizes the bank. Using the data in Table 5a an estimated 173 m^3 of sediment was captured and prevented from erosion as a direct result of cedar revetments. This is equal to approximately 23 large dump truck loads of sediment.

Most of the cedar revetments successfully withstood an estimated 50-year flood after being in place for only 3 to 4 years. Bank erosion during this event was significantly reduced along revetted reaches as compared to non-revetted reaches. There are some areas on the outside bends of sharp (about 90º) meanders, with high (> 2 m), steep banks, where the revetments did not stay intact. This seems to indicate that banks subject to extremely high shear stresses during floods are unsuitable for cedar revetment. However, it is possible that if more time had elapsed between the installation and flood, or if the flood had been a smaller event, the revetments may have performed better in these locations. This is an open question that cannot be addressed with the data discussed in this thesis.

From the sUAS imagery and ground observations it is possible to create a list of “revetment rules” for practitioners to consider when employing this bank stabilization approach: 1) The majority of the revetment retains sediment and stays in place during high flow events. 2)

During high flow events the upper part of the bank may recede, but the slumping material gets caught within the branches of the cedars and the bank angle becomes shallower. This causes a shelf (or lateral bar) to form around and below the cedars in the water. 3) The shelf in rule 2 is accommodation space for slump material in the future and keeps sediment from washing away. 4) Revetment on a sharp, outside bend is likely to fail during high flow events when there is enough stream length before the bend for water to concentrate and momentum and velocity to increase beyond a threshold value such that shear stresses overcome the holding force of the anchor. 5) Revetments decrease velocity near the bank. This is seen both visually and quantitatively. Based on these observations and calculations cedar revetment is a bank stabilization method worth implementing more broadly in streams similar to the Lea and Sinclair reaches of Riceford Creek. Specifically, these streams are low gradient (average slope around 0.1), meandering, riffle/pool, alluvial channels with broad flood plains occurring in mid-temperate latitudes.

Rosgen's BEHI method is not a good predictor of erosion in Riceford Creek when employed in its standard form. However, our analysis indicates that regrouping the BEHI scores into two broad groups representing "Extreme to High" and "Moderate to Very Low" was a useful method for prioritizing stream banks for revetments and predicting the shear forces that act on the banks during a large flood. Additionally, BEHI serves the purpose of focusing field observations prior to revetment in such a way that can build experience that will yield better subjective judgments about how to prioritize banks. A more focused future study of Rosgen's BEHI method in prioritizing cedar revetments could refine these conclusions and yield a more robust conclusion.

Future studies of Riceford Creek would benefit from the use of erosion pins to further quantify bank erosion rates. This study was an examination of the shorter-term (after installation) efficacy of cedar revetments. Re-evaluating these sites in 5 or 10 years would be worthwhile to look at the longer-term success of the methodology. It would also be beneficial to collect velocity profiles along banks during a high flow event to better understand how flow dynamics in the stream change around the revetments.

Cedar revetments are significantly cheaper than traditional bank stabilization and restoration techniques. They are also quicker and easier to install, require little training for installation, and have high rates of revetment success. The relatively low cost of cedar revetments, as compared to other commonly used stream restoration methodologies, also allows one to err on the side of installing a revetment when objective or subjective criteria are unclear in terms of evaluating a stream bank's potential for erosion. This makes it feasible for workers lacking in-depth training in fluvial geomorphology and stream restoration practices, such as the field technicians from the local Soil and Water Conservation District who led the implementation of revetments at Riceford Creek, to undertake stream bank stabilization without the necessity of depending on expensive stream restoration consultants, without necessarily compromising the overall success of the project. Furthermore, revetment installation does not require the use of heavy machinery within the stream channel or along the banks. This greatly reduces the impact of the installation on aquatic communities and reduces or eliminates permitting requirements in many localities. Based on the results of this study the further use of cedar revetments to mitigate stream bank erosion is warranted in similar settings.

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